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# Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities

## Volume 2. Baltimore Canyon Trough and Environs - U.S. East Coast

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## PREFACE

This document is Volume 2 of a series of reports entitled "Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities." Volume 2 provides an analysis of the "Baltimore Canyon Trough and Environs - U.S. East Coast." The report presents a geological description of the Baltimore Canyon Trough region, including regional and local structural settings, geomorphology, geological history, stratigraphy, and physical properties. Included also is a discussion of bottom simulating acoustic reflectors, sediment acoustic properties, distribution of hydrates within the sediments, and the relation of hydrate distribution to other features such as salt diapirism. The formation and stabilization of gas hydrates in sediments are discussed in terms of phase relations, nucleation, and crystallization constraints, gas solubility, pore fluid chemistry, inorganic diagenesis, and sediment organic content. A depositional analysis of the area is discussed in order to better understand the thermal evolution of the locality and to assess the potential for thermogenic hydrocarbon generation.

Project Manager
Gas Hydrates

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## Acknowledgments

Geoexplorers International, Inc. and the authors are very grateful to the U.S. Department of Energy - Morgantown Energy Technology Center for an opportunity of, and active involvement in, the gas hydrate research program. Moreover, cooperation with DOE's METC professionals is very pleasant and relevant discussions are fruitful. We wish to express special thanks to Rodney Malone and Kathryn Dominic for many helpful suggestions that have been considered in the manuscript. Exceptional appreciation is acknowledged to Charles Komar for his kindness and very effective action in publication of this report.

The critical reviews of the manuscript by Bernard Rudloff, Mark Ciesnik, Patrick Finley and the graphical illustrations drafted by Margaret Krason (all of Geoexplorers International, Inc.) are also of special contribution to this report.

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# BASIN ANALYSIS, FORMATION AND STABILITY OF GAS HYDRATES IN THE BALTIMORE CANYON TROUGH AND ENVIRONS

## EXECUTIVE SUMMARY

Gas hydrate formation and stability can be determined either by comparison with the relevant model or by thorough basin analysis. Since the relevant model is not available, particularly for offshore environments, the basin analysis and the gas hydrate formation assessment has been applied as a concept-oriented approach in this study.

The study region which includes offshore of New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina, is referred to in this report as the "Baltimore Canyon Trough and environs" or for short "Baltimore Canyon Trough." This study and the report are a part of a much larger project contracted from Geoexplorers International, Inc. by the U.S. Department of Energy - Morgantown Energy Technology Center (DOE - METC).

Principal sources of data for this report are seismic surveys and results from offshore exploratory drill holes. Petroleum companies have conducted seismic and drilling studies in the region, particularly in the shallower continental shelf areas. However, much of this data remains proprietary. Government agencies and research institutions have produced a vast amount of data on the study region which is available for the public and has been used extensively for this study.

In the Baltimore Canyon Trough and environs, the gas hydrate occurrences are documented seismically from the lower continental slope and upper continental rise, at 2,000 - 3,600 m of oceanic water. Occurrences of gas hydrates are implied from the presence of bottom simulating reflectors (BSRs). Three classes of BSRs, differing in continuity and strength of the reflection, are recognized in the study region. Strong, continuous reflectors are identified on sections from areas between the Hudson and Wilmington canyons. To the northeast and southwest of this area, more diffuse and discontinuous BSRs predominate.

Although the continental shelf areas in the study region have been extensively drilled commercially and are thus well understood, these shallow areas have limited potential for gas hydrates. The entire continental shelf is under 100 m of water, but the shelf edge is conventionally defined by the 200 m isobath. This area is not conducive for gas hydrate formation and preservation because temperatures are too high and pressures are too low.

The continental slope and upper continental rise (200 m to 3,500 m below sea level) have more potential for hydrate accumulation, but less data are available for assessment. The geological history of the continental slope and rise have a direct bearing on gas hydrate potential.

The eastern U.S. Continental Margin within the study region is characterized by an early period of pre- and syn-rifting sedimentation and a period of tectonically driven sedimentation during Middle through Late Triassic and Early Jurassic, followed by an uninterrupted, prolonged period of tectonic quiescence and steady thermal subsidence. These conditions led to accumulation of a very thick sequence (up to 15,000 m) of deltaic to shallow marine sediments, deposited during Triassic through Tertiary time. This sequence includes a lower Cretaceous fringing carbonate platform at the seaward edge of the margin. The shelf edge reheated during the middle Tertiary regression accompanied by erosion. The first post-regressive Miocene units prograde seaward over older rocks.

Later sedimentation was dominated by turbidite deposition. During late Tertiary through Pleistocene time, a dominant fraction of the sedimentary clastic input was channeled toward the shelf edge, which prograded fairly rapidly over the remnants of Late Cretaceous to early Tertiary paleoshelf edge. The inherent adaptability of the clastic apron led to widespread gravity failure and redeposition of a large amount of sand, silt, and mud (up to 3,000 m thick) over the lower continental slope by turbidity currents and slumping. The introduction of sand into a silty and muddy sequence at the base of the continental slope provided future gas hydrate host rocks.

Rapid changes in sediment thickness caused by widespread submarine erosion, slumping, and turbidite deposition may help explain the discontinuity observed in some BSRs. When sediments are rapidly added or removed from an area by these processes, the thermal regime of the area is altered. The disturbed thermal regime reequilibrates to one stable for the new sediment load. The adjustment of heat flow and geothermal gradient displaces the zone of gas hydrate stability vertically. The vertical shift of gas hydrate stability zones could possibly result in isolated pockets of massive and nodular hydrates with different seismic properties than the surrounding disseminated gas hydrates.

The organic contents of sediment samples from the study region are marginally sufficient for biogenic methane generation. A notable exception is an organic rich Miocene age sediment layer which may serve as a source for biogenic methane.

Calculated organic and clastic sediment flux for areas throughout the study region likewise suggest organic carbon levels which are marginally sufficient for biogenic methane generation, with the possible exception of the Hatteras Outer Ridge, where richer conditions may exist.

Maturity models of the region suggest that thermogenic sources for methane in gas hydrates are unlikely. Depths of mature source beds are such that extensive vertical migration would be necessary for accumulation in the gas hydrate stability zone. Evidence suggests a dominantly biogenic source of gas for gas hydrates in this region.

Estimates of the areal extent of gas hydrates in the study region range from 30,000 $km^2$ to 50,000 $km^2$ based on seismic evidence from areas overlain by 2,000 to 3,600 m of water. Assuming that gas hydrates occupy all of the sedimentary pore volume, a gas hydrate zone one meter thick may contain up to $2.9 \times 10^{11}$ $m^3$ or 21 trillion cubic feet (TCF) at 0°C and one atmosphere pressure for the area underlain by BSRs.

Gas may be trapped in pore spaces below the lower limit of the gas hydrate stability zone. The thermal reequilibration of the sediments in response to sedimentation may produce relief on the lower surface of the gas hydrate zone. This relief may provide closure necessary for accumulation of gas beneath the impermeable gas hydrate. Such a reservoir beneath a gas hydrate seal with an area of one $km^2$ and six meters of closure could contain $10^5$ $m^3$ or 3 MMCF of gas.

TABLE 1. Summary Data of Basin Analysis, Formation and Stability of Gas Hydrates in the Baltimore Canyon Trough and Environs, is located in the pocket at the end of the report.

## INTRODUCTION

As part of the U.S. Department of Energy (DOE) - Morgantown Energy Technology Center (METC) research program on gas hydrates, Geoexplorers International, Inc. is preparing a series of reports on the geological evolution of confirmed and potential gas hydrate-bearing sites. To date, twenty-four offshore sites have been identified by DOE (Appendix 1) based upon the compilation of Kvenvolden and McMenamin (1980). The first report covered the Blake - Bahama Outer Ridge, a major bathymetric structure seaward of the Carolina Trough, where gas hydrates have been recovered in Deep Sea Drilling Project (DSDP) cores. That report (Krason and Ridley, 1985) also discussed the chemical conditions which stabilize gas hydrates and attempted to place them in a geological context. In particular, the following were discussed as potentially important factors in promoting gas hydrate growth and stability:

1. Anoxic conditions near the sediment surface to optimize organic matter preservation.

2. Sufficient organic matter flux through the water column to sustain microbial methanogenesis within the sedimentary sequence.

3. Bottom water temperature within the stability field of gas hydrate formation.

4. Sufficient methane production to supersaturate the pore fluid with gas to promote initial gas hydrate nucleation.

The following factors are important in determining the distribution of gas hydrates within the sedimentary sequence:

1. The thermal gradient, which is determined by sediment accumulation rate, lithology, compaction, and heat flow.

2. The rate of methane production and the permeability of the sediment to gas flow as a function of time.

3. The nature of the pore system, i.e. water versus gas dominated pore space.

4. The relative amount of available "structured" water and "bulk" water in pore spaces.

5. Physical conditions at the lower boundary of the gas hydrate stability zone.

These conditions apply to gas hydrate formation in general. The reader is referred to the Blake - Bahama Outer Ridge report for details which are not repeated here (Krason and Ridley, 1985).

This report describes the geological evolution of the Baltimore Canyon Trough and environs (Figure 1), designated as Site No. 2 by DOE. At this site, the presence of gas hydrates is suggested by a bottom simulating reflector (BSR) on many detected multichannel seismic profiles. To date, no samples of gas hydrates have been recovered from this region.

## Data Base

The Baltimore Canyon Trough is the most extensively studied sedimentary basin in the Atlantic margin of the United States largely because of its petroleum potential. Exploration has been restricted to shallow water (<1,000 m). Geological data on the Baltimore Canyon Trough in areas of deeper water are from seismic surveys and four Deep Sea Drilling Project (DSDP) sites. Where commercial drilling has taken place, geological control is good, but data from the deeper continental slope and rise, where gas hydrates are likely, are much more limited.

Much of the seismic data acquisition and interpretation has been carried out by the U.S. Geological Survey and was presented in a long series of publications (see references). Seismic stratigraphic information has been supplemented by two deep test wells, COST B-2 and COST B-3 drilled by the Continental Offshore Stratigraphic Test Group (COST), a consortium of major oil companies and the Federal Government. In addition, information was released to the public in 1982 for the following wells drilled by oil companies: Exxon 500-1, Exxon 599-1, Exxon 684-1, Exxon 728-1, Exxon 816-1; Mobil 17-2, Mobil 544-1; Murphy 106-1; Tenneco 495-1, Tenneco 642-2, Tenneco 642-3; Hom 676-1, Hom 855-1; Gulf 857-1; Texaco 598-1, Texaco 598-2, Texaco 598-3; Shell 632-1. This information supplemented that previously released from Shell 272-1, Shell 273-1, and Gulf 718-1. The location of these wells, shown in Figure 2, indicates the limited well coverage relative to the areal extent of the Baltimore Canyon Trough (Figure 1). However, several shallow wells have been drilled in other parts of the Baltimore Canyon Trough and environs by the Atlantic Slope Project (ASP 7, 8, 10, 13, 14, 15, 22, 23) and the Atlantic Margin Coring Project (AMCOR 6007, 6011, 6020, 6021). Whereas the ASP wells were drilled in up to 1500 m of water, the AMCOR wells were sited in less than 300 m of water and are thus of limited use in gas hydrate studies. Additional well information may be obtained from Sites 105, 106, 107, and 108 of DSDP Leg 11. Important USGS seismic lines in this area are numbered, from south to north, 29, 11, 28, 3, 27, 10, 26, 6, 25, 2, 9, 23, which transect the continental margin, and 15, 34, 35, 13, which parallel the margin. Numerous additional seismic lines are available from Lamont - Doherty Geological Observatory (LDGO), Woods Hole Oceanographic Institute (WHOI) and University of Texas, Marine Science Institute (UTMSI). The location of these lines has been compiled by Ewing and Rabinowitz (1984) and most of these, together with the USGS data, are available from the National Geophysical Data Center, Boulder, Colorado (Appendix).

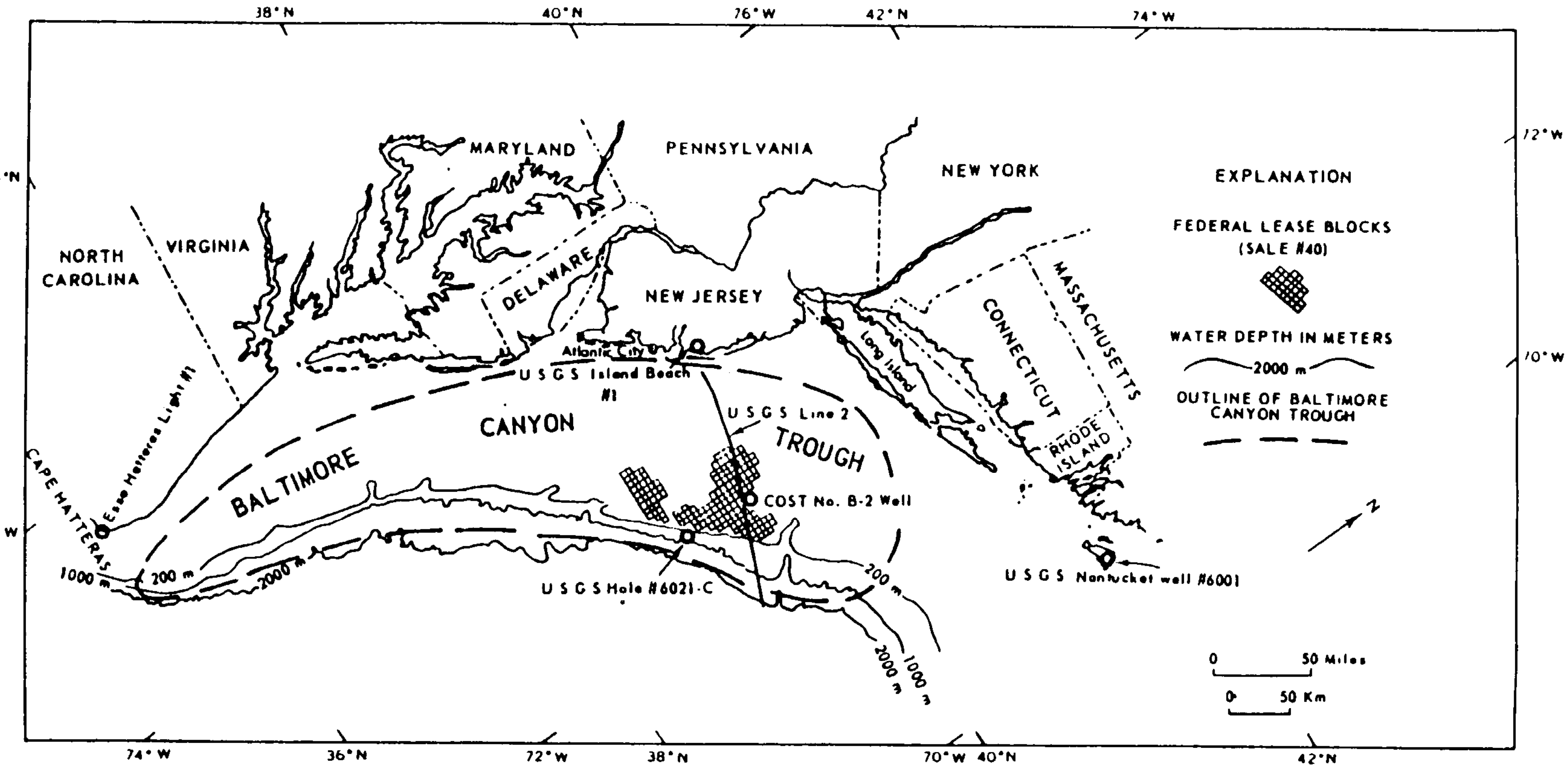



**Figure 1. LOCATION MAP SHOWING THE BALTIMORE CANYON TROUGH AND ENVIRONS**

Figure 2 is in area of Lease Sale #40.

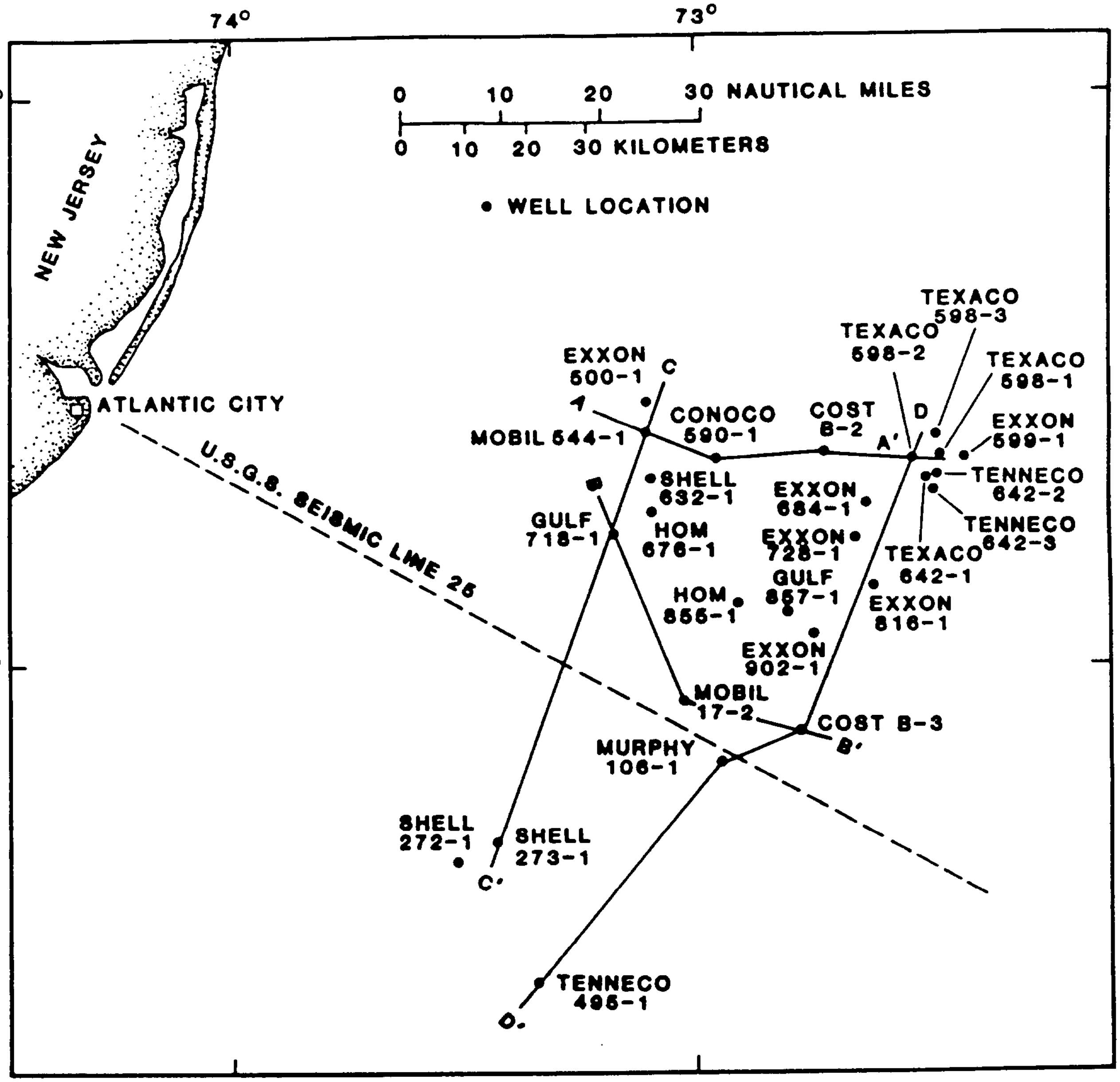



**Figure 2. LOCATION OF WELLS ON SHELF AND SLOPE, BALTIMORE CANYON TROUGH REGION, U.S. ATLANTIC MARGIN**

**After Libby - French (1983)**

## Gas Hydrates in Nature

Gas hydrates are solid-state clathrates, which develop when gas dissolved in water assumes a crystalline, ice-like form. Since their discovery in 1810 (Davy, 1811), a plethora of papers have been published describing the synthesis of new gas hydrates. Their importance in natural phenomena and economic processes cannot be overemphasized. Gas hydrates clog natural gas pipelines, form the basis for an important sea water desalination process, and are crucial in freon coolants. The hydrates of certain gases have been observed spectrally in interstellar space, in comet heads, and on satellites of the outer planets, thus they are of fundamental importance in stellar processes. Gas hydrates appear to be critical to the stabilization of some protein molecules in living organisms and have been proven important to the process of anesthesia.

From the geologist's perspective, interest in gas hydrates involves understanding their formation and limits of stability in suitable geological environments, i.e. permafrost regions and the submarine realm. In these environments the dominant hydrate is methane hydrate, although the potential exists for the stabilization of $C_2$ - $C_4$ hydrates. The development of gas hydrates within shallow sediments not only provides a vast reservoir of potentially producible hydrocarbons, but also an efficient seal for trapping gas beneath. Consequently, a better understanding of natural gas hydrate stability is essential to any economic assessment of this unconventional energy resource.

## PART I

## BASIN ANALYSIS

### Regional Structural Setting

The Baltimore Canyon Trough is a major sedimentary basin underlying the Atlantic Continental Margin of North America (Figure 1), offshore from the states of New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina. To the northeast are the Scotian and Georges Bank Basins and to the south lie the Carolina Trough and Blake Plateau Basin (Figure 3). These basins developed throughout Mesozoic and Cenozoic time and have no expression in the present-day configuration of the shelf and the continental slope and rise. Their presence has been determined from geophysical data supplemented with deep well information and from onshore outcrops.

The western Atlantic Continental Margin is a classic "passive" margin and is generally considered the type example of geologic features developed during continental rifting and subsequent ocean formation (Bally, 1980). The same margin represents the western part of the initial rift zone developed between North America and Europe prior to and during their early separation, roughly dated at 180 m.y. The basement is composed of a series of fault-bounded blocks made up of Precambrian and Paleozoic rocks, which were attenuated to various degrees prior to the ocean development. This crustal thinning resulted in major iosostatic adjustments of the fault blocks throughout the Mesozoic and Cenozoic and loading of the margin with sediment eroded from the blocks themselves and from the continent lying to the west (Poag, 1978). Thus, the subsidence of the margin is a result of isostatic adjustment, thermal contraction, and sediment loading. The margin is also cut by a series of major fracture zones, principally perpendicular to the margin. These transverse fractures were developed during the initial period of continental crust attenuation and were subsequently propagated into the opening Atlantic Ocean. They can be used to reconstruct the Mesozoic and Cenozoic poles of rotation between the North American Plate and the Eurasia Plate. Most of the fractures can be traced from the continental shelf to the present-day mid-Atlantic Ridge. The early stages of rifting can be recognized on seismic sections as half grabens developed within the continental basement under the present-day shelf. Beneath the Baltimore Canyon Trough these grabens occur at 12,000 - 15,000 m beneath sea level. By analogy with onshore basins, the half grabens are assumed to be filled with Triassic continental red bed deposits and associated volcanic rocks. A modern day analogy is assumed to be the East African Rift Zone (Manspeizer, 1980). The main phase of rifting is represented by a marked unconformity, the so called post-rift unconformity, above which are found Triassic to Jurassic evaporites representing the chemical deposits from a restricted early Jurassic seaway. During further rifting, a

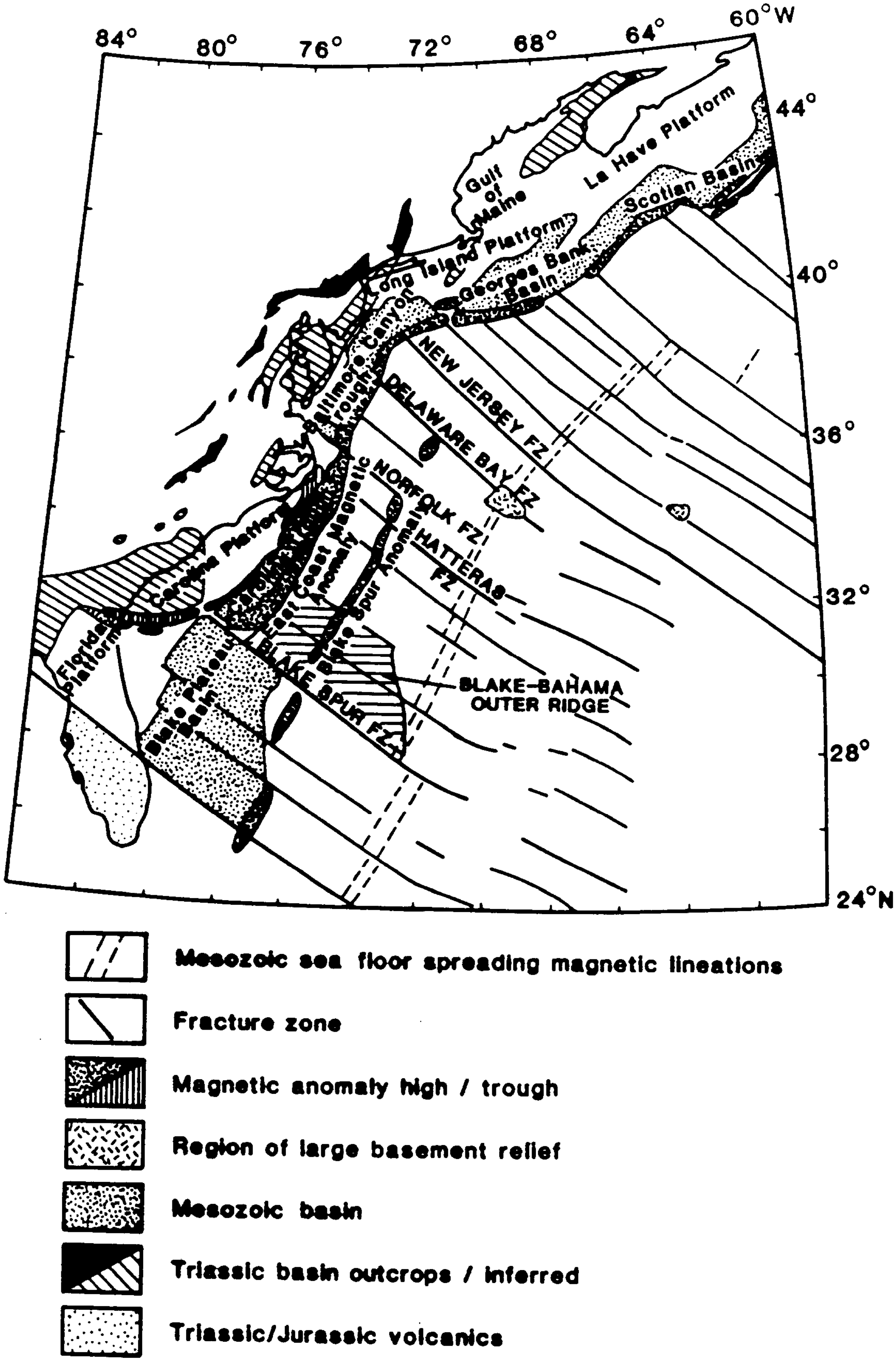



**Figure 3. TECTONIC FEATURES OF THE EASTERN CONTINENTAL MARGIN OF NORTH AMERICA**

**After Grow (1981)**

thick wedge of Mesozoic and Cenozoic sediments was built out onto the subsiding margin, as major deltas prograded across the continental shelf. Carbonate buildups, reefs, oolitic sediments, and micritic limestone marked the shelf slope break. Occasionally, the deltaic sedimentation was interrupted by more open marine conditions.

The focus of sedimentation was determined by the relative rates of subsidence of the major fault blocks and the position of transform faults. Thus, the major sedimentary basins, separated by shallow marine platforms, are generally elongated parallel to the present-day margin, and most contain more than 10,000 m of sediment in their deepest parts.

The regional structure of the margin has been reconstructed through integration of seismic (Behrendt et al., 1974; Grow and Schlee, 1976; Schlee et al., 1976, and others), magnetic (Klitgord and Behrendt, 1979) and gravity (Hutchinson, et al., 1983) data. Beneath the present shelf, the crust is considered to be continental in nature, with low amplitude magnetic anomalies. However, beneath the outer shelf and upper slope, where the greatest thickness of sediments is found, the crust changes character, becoming progressively thinner and more oceanic in nature. A distinctive magnetic anomaly, East Coast Magnetic Anomaly (ECMA, Figure 4), is observed in this region and has been interpreted as a transitional contact zone between oceanic crust to the east and continental crust to the west (Keen, 1969). This region also corresponds to a positive free-air gravity anomaly (Watts, 1980). Seaward of the ECMA is observed a basement high on gravity, magnetic, and seismic data. This high may represent a tilted block of oceanic crust or an extinct spreading center and appears to have been the site of later carbonate buildups. However, detailed analysis of USGS seismic line 25 in the slope vicinity (Grow et al., 1979) suggests the ridge may either not exist or be deeper (>13 km) and narrower than previously considered. Hence, the nature of the basement high should be considered undetermined to date.

Within the region of the Baltimore Canyon Trough, the process of sedimentation was interrupted occasionally by igneous activity in the form of major mafic intrusions, e.g. Great Stone Dome, and intrusions near Cape Charles and Cape Henry. The intrusions are evident on magnetic anomaly maps (Klitgord and Behrendt, 1979). Salt intrusions are also identified along the line of the ECMA, presumably as a result of remobilization of Lower Jurassic evaporites.

## Sedimentation Patterns

Most of the sedimentary basins along the U.S. Atlantic Continental Margin had received almost all of their sediment supply by the end of the Pliocene. However, the patterns of sediment distribution through the Pleistocene and Holocene are important because, at least in some areas, present-day gas hydrates are likely to be found within these sediment units.

During Pleistocene to Holocene time, especially during lowstands of sea level, much of the present continental shelf was exposed. Sediments deposited on the shelf were thus of lagoonal, fluvial, and marginal marine character and much of the shelf was by-passed, resulting in deposition on the continental slope and rise. The present continental shelf is an area of relict sediment

FIGURE 4. Major Tectonic Features Associated With the Baltimore Canyon Trough, is located in the pocket at the end of the report.

distribution, largely involving sediments of Pleistocene age. Only in limited shoreline areas is active deposition occurring, resulting in slow progradation of sands over older Pleistocene gravels and coarse sands. The present-day continental slope and rise are not sites of biogenic carbonate deposition. However, the proportion of clastic material increases once more on the lower continental rise and abyssal plains.

Several studies have shown that the present distribution and dispersal patterns for sediment is a disequilibrium situation (Knebel, 1984), whereby the sediment is not in equilibrium with the present current pattern. Along the margin sediment is transported by: 1) turbidity currents, 2) slumping and sliding, 3) turbid-layer transport.

The continental margin, particularly in the environs of the Baltimore Canyon Trough, is dissected by many large submarine canyons (Figure 5) which act, and have acted, as conduits for sediment transport from the shelf onto the continental rise and abyssal plain. Thus, this transport mechanism effectively by-passes the continental slope but deposits large volumes of sand, silt, and clay in the hemipelagic and pelagic environment of the continental rise and abyssal plain (McGregor, 1979).

Sediment transport and deposition may also be accomplished through large-scale submarine slumping, particularly on the steeper parts of the continental slope. Major slumps and slides can easily be identified on seismic profiles perpendicular to the margin (Hollister et al., 1972). They usually carry fine-grained slope sediment into somewhat deeper water. Turbid-layer transport involves the movement of currents, made turbid by sediment suspension, close to the ocean floor. This mechanism is capable of transporting large volumes of fine-grained sediment from the shelf onto the continental slope where it may be further reworked into finely laminated contourites through the actions of contour currents, e.g. western boundary undercurrent. The latter is active in shaping the slope and rise south of Cape Hatteras but appears to be less effective northwards.

Thus, the post-Pliocene depositional patterns have involved a complex interplay of sedimentation, non-deposition, and erosion. The most active depocenters are those where large volumes of clastics are channelled down submarine canyons. For instance, DSDP Leg 11, Site 106 cored thick turbidite sands in 4,500 m of water, ponded between the lower continental rise hills and the shallower rise (Hollister et al., 1972). Between Baltimore and Washington Canyons, a series of pronounced ridges on the middle and lower slope contain over 600 m of mass-moved, pre-Pleistocene sediment. A similar depocenter exists on the upper slope adjacent to Albemarle Sound (McGregor, 1979).

These various features can have implications for gas hydrate formation in post-Pliocene sediments. In the case of slumping, sliding, and turbidity current activity, the sediment may be disrupted sufficiently to effectively disperse whatever gas hydrates had developed within the sediment. Obviously, the extent of this process depends upon the timing of movement relative to the present and the extent to which hydrate conditions can be reestablished in the new depositional environment.

## Location and Submarine Geomorphology

The region of potential hydrate formation discussed in this report lies beneath parts of the continental slope and upper rise offshore from North Carolina, Virginia, Delaware, Maryland, New Jersey and New York, essentially between Cape Hatteras and Cape May (Figure 5). The location of gas hydrate zones, based on their seismic expression was studied by Tucholke et al. (1977). However, because the potential range of gas hydrate stability can be extended to about 500 m water depth, the upper continental slope is also included in our considerations, which therefore involve the easternmost parts of the Baltimore Canyon Trough. In discussion of the evolution of the Trough, we consider it necessary to use data from wells located on the continental shelf, which extends from the shoreline to a water depth of about 150 m. The shelf is relatively flat with slopes in the order of 1 - 1.5°. The shelf steepens near the shelf slope transition and the continental slope itself is 3 - 5 km wide, lying between 150 - 2,000 m water depth, with 3 - 6° slopes. The slope grades gently into the continental rise at about 2,000 m depth where the gradient decreases to 0.06 - 1.4° down to 5,000 m depth. At greater than 5,000 m water depth the continental rise merges with the Hatteras abyssal plain, a flat-lying feature with gradients less than 0.06°. Two topographic profiles indicating these various regimes are shown in Figure 6A, B.

The continental margin is also dissected by a number of major submarine canyons at the shelf slope break. From the north to south these are: Hudson, May, Hendrickson, Toms, South Toms, Berkeley, Carteret, Lindenkohl, Spencer, Wilmington, Baltimore, Washington, and Norfolk. Their topographic expression can be seen on Figure 5 and on sections parallel to the continental margin (Figure 7A, B, C, D). With increasing depth, the topography becomes more subdued as the sea floor itself becomes more gentle, partly because their lower reaches are filled with turbidite sediments. The spectacular topographic expression of the canyons on the upper slope testifies to their recent activity as conduits for sediment transport. On the lower slope and rise, the Wilmington and Hudson valleys have deeply dissected the margin.

The area under discussion also includes the Baltimore Canyon Trough, a major sedimentary basin underlying the shelf and upper slope. The basin is about 600 km long between 35 and 40° north and spreads eastward to 72° west. It is widest off the New Jersey coast where its maximum width (200 km) is also the area of maximum sediment thickness (15,000 m). The seaward border is a basement ridge of undetermined character and origin. The northern margin is the Long Island Platform, and the southern margin is the Cape Fear Arch. The basin has an onshore extension termed the Salisbury Embayment and other connected embayments are the Raritan and Albemarle Embayments.

## Stratigraphy

Stratigraphic relationships in this region are best documented in the areas of the present shelf and upper continental slope, as a result of hydrocarbon exploration drilling (Libby-French, 1984), but are less well

FIGURE 5. Bathymetric Map of the Continental Margin in the Vicinity of Baltimore Canyon Trough, is located in the pocket at the end of the report.

FIGURE 6A. Topographic Profile Perpendicular to U.S. Atlantic Continental Margin in Vicinity of Baltimore Canyon Trough, is located in the pocket at the end of the report.

FIGURE 6B. Topographic Profile Perpendicular to U.S. Atlantic Continental Margin in Vicinity of Baltimore Canyon Trough, is located in the pocket at the end of the report.

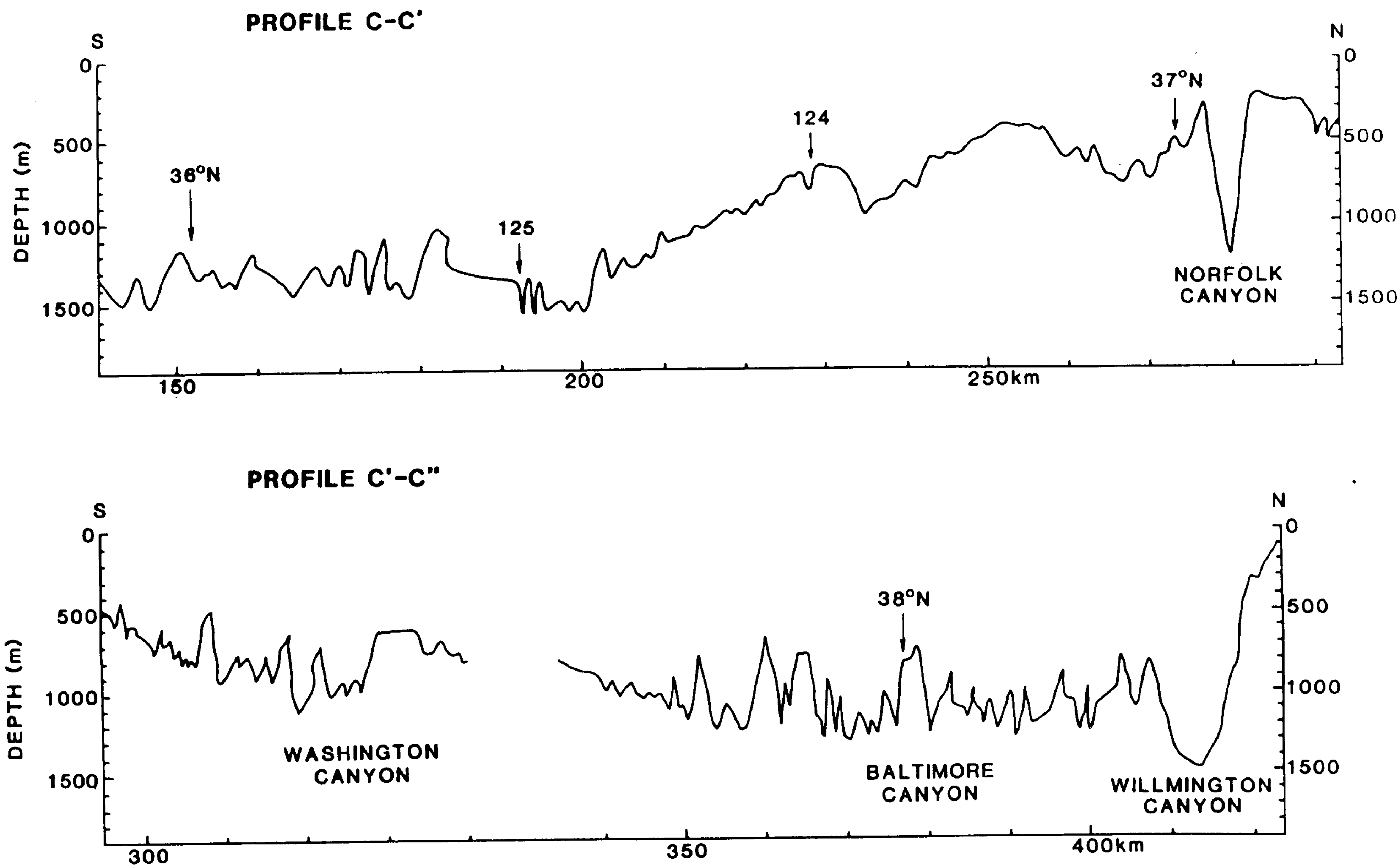



**Figure 7A. TOPOGRAPHIC PROFILES ALONG ATLANTIC CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

Profiles C-C' and C'-C" are located on Figure 5. Profiles are based on bathymetric data calculated from seismic section in McGregor (1979). The profiles parallel the continental slope which is dissected by numerous submarine canyons.

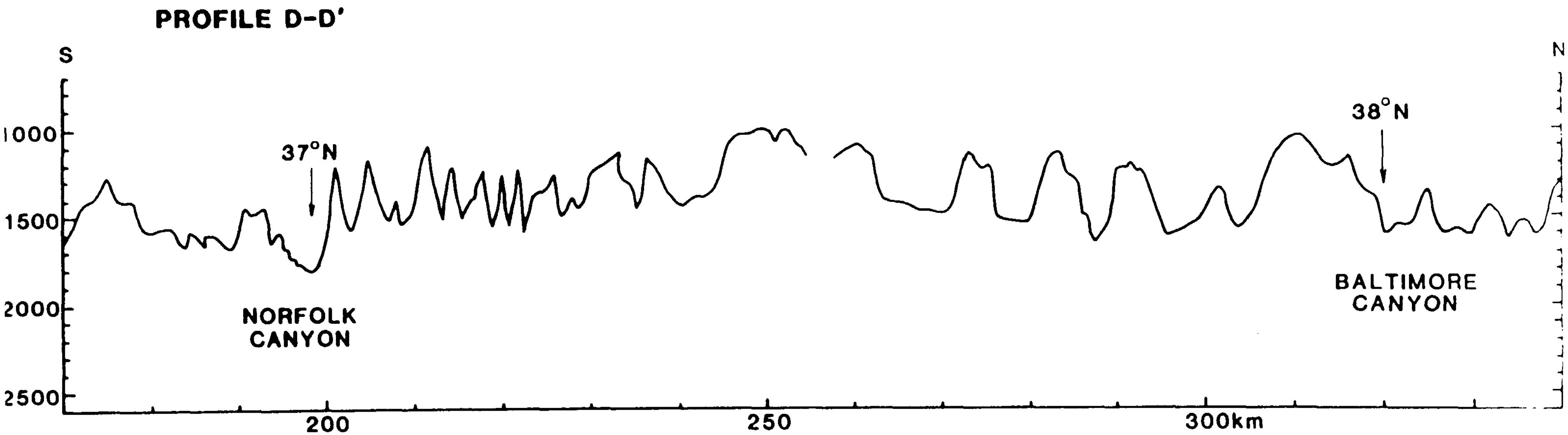



**Figure 7B. TOPOGRAPHIC PROFILE ALONG ATLANTIC CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

Profile D-D' is located on Figure 5. Data are after McGregor (1979). The profile parallels the lower continental slope.

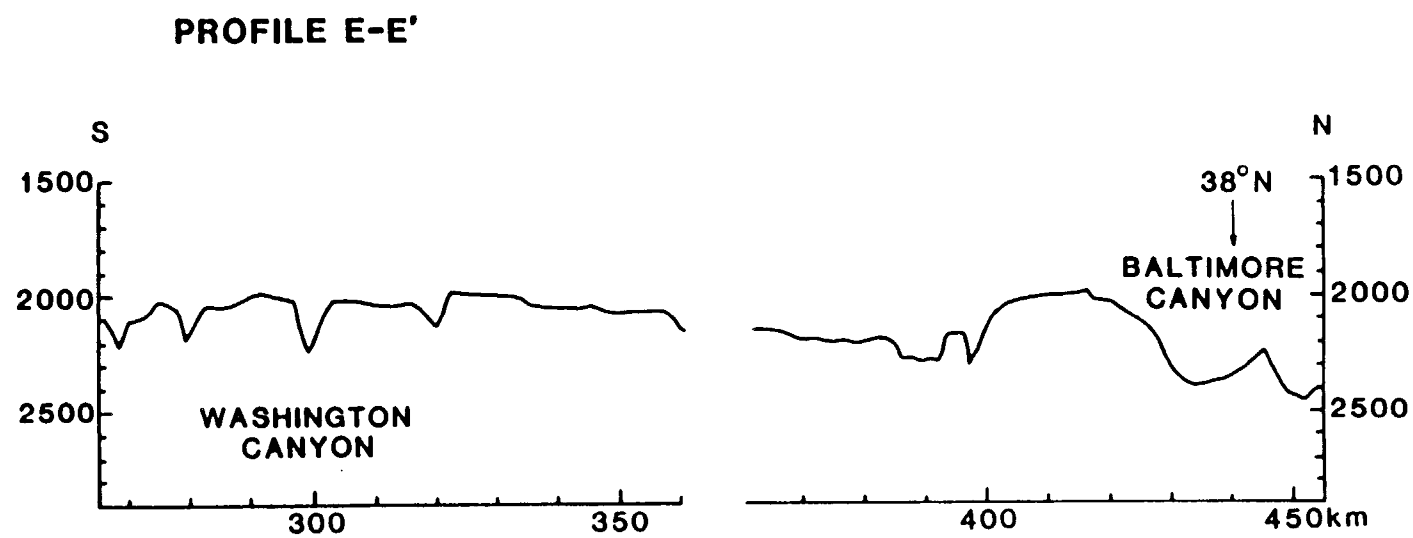



**Figure 7C. TOPOGRAPHIC PROFILE ALONG ATLANTIC CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

Profile E-E' is located on Figure 5. Data from McGregor (1979). The profile parallels the continental rise.

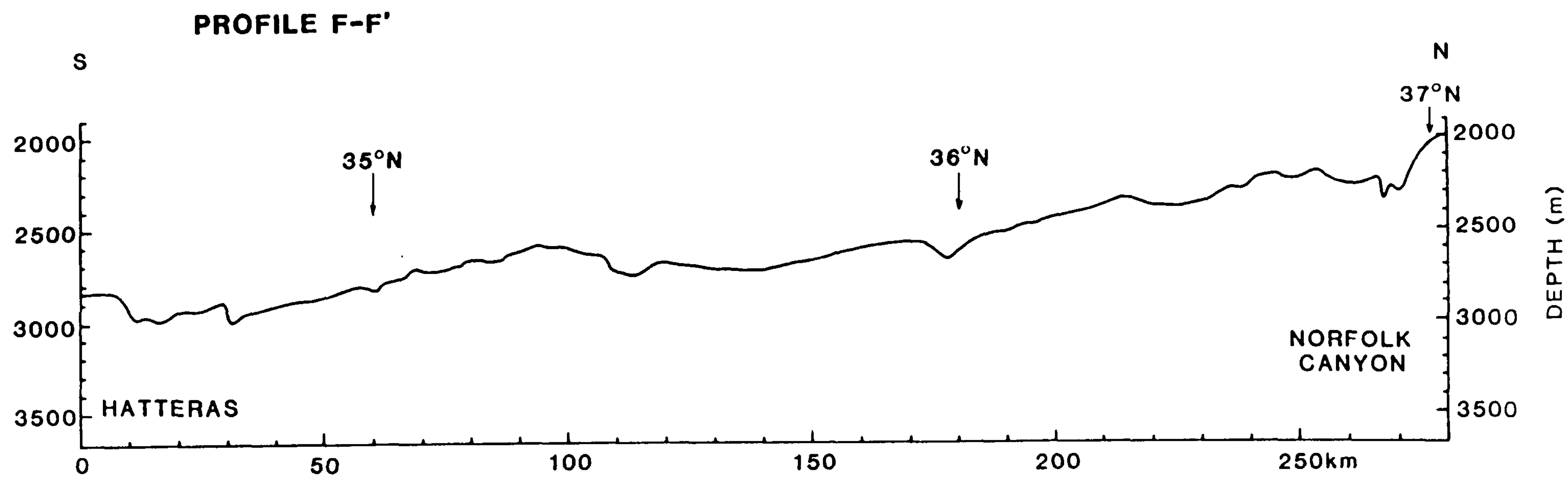



**Figure 7D. TOPOGRAPHIC PROFILE ALONG ATLANTIC CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

Profile F-F' is located on Figure 5. Data from McGregor (1979). The profile parallels the continental rise.

documented on the lower continental slope, rise, and abyssal plain (Poag, 1978). In order to provide a comprehensive view of the stratigraphy of the margin we include a review of the known stratigraphic relationships beneath the shelf and upper slope beneath which lies the great wedge of Mesozoic and Cenozoic sediments of the Baltimore Canyon Trough. The configuration of the margin was different during Late Jurassic and Early Cretaceous time than it is today because the shelf edge was some 20 - 30 km east of its present location. Thus, the present upper slope is underlain by a considerable thickness of Mesozoic shelf sediments.

The stratigraphic framework is discussed in terms of the lithofacies characteristics either observed from sediment cores or deduced from seismic data. These characteristics are then used to reconstruct the environments of deposition through Mesozoic and Cenozoic time. A seismic stratigraphic interpretation across the margin and through the Baltimore Canyon Trough is shown in Figure 8. This section illustrates the gross stratigraphic relations, particularly the lateral variations in sediment thickness and how it has been controlled in part by the Mesozoic paleoshelf edge. In addition, it indicates the lateral change from continental basement in the west to oceanic basement in the east. A north-south cross section is shown in Figure 9.

### Lithofacies

Libby-French (1984) has interpreted the various formations of the Baltimore Canyon Trough as homotaxial equivalents of formations described from the Scotian Basin; the formation names from the Scotian Basin are formally preferred.

The Upper Jurassic rocks have not been completely sampled, but are considered equivalent to the Mohawk Sandstone, Mic Mac Shale, and Abenaki Limestone. Most of this Jurassic section is equivalent to the Mohawk or Mic Mac. Mic Mac may be as young as Barremian. The Mic Mac equivalent is a gray to black, micaceous shale and siltstone sequence with sporadic interbeds of fine to coarse sandstone (<15 m thick), particularly evident at the COST B-3 well. The lithology suggests the Mic Mac is a pro-deltaic deposit.

The lateral age equivalent of the Mic Mac is a very coarse sand, 60 - 90 m thick which is easily identified in the Conoco 590-1, Texaco 598-2, COST B-2, and Mobil 544-1 wells. The textures and lithologies are not consistent with a pro-deltaic environment; the Mohawk equivalent may represent delta plain deposits.

On the Scotian shelf the Abenaki Formation is a carbonate sequence representing a widespread marine reef complex active during Late Jurassic and Early Cretaceous time. Based on seismic evidence (Sheridan, 1974; Schlee, 1976), an equivalent carbonate buildup is believed to exist beneath the present-day slope in the Baltimore Canyon Trough region. Whether the build-up is a true ecologic reef, a lime mud mound, or an oolite bank is undetermined; the structure is simply termed a stratigraphic reef. Core from the COST B-3 well indicates the carbonate unit is a fossiliferous, oolitic grainstone to packstone assemblage interpreted in this locality as a back-reef deposit.

The Lower Cretaceous is represented by equivalents of the Missisauga, Naskapi, and Logan Canyon Formations in ascending order. The abundance of thick, bedded sandstone distinguishes the Missisauga from the Mic Mac Shale

FIGURE 8. Interpretation of Seismic Profile 25 Across the Continental Margin in Vicinity of Baltimore Canyon Trough, is located in the pocket at the end of the report.

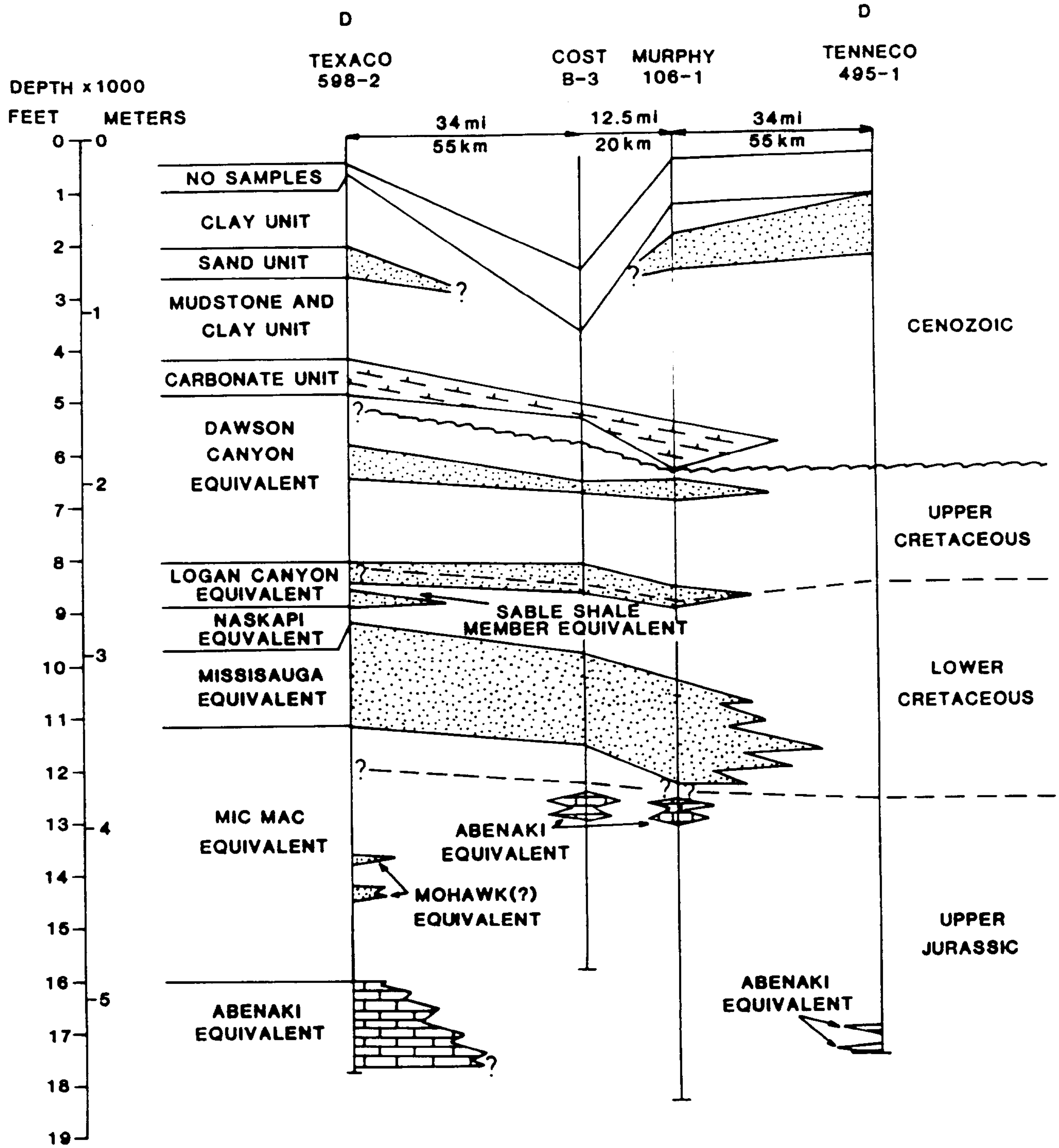



**Figure 9. NORTH-SOUTH CROSS-SECTION THROUGH WELLS ON UPPER SLOPE OF BALTIMORE CANYON TROUGH**

The formation names are those from Scotian Shelf region. Data after Libby-French (1984).

equivalent. The sandstones are interbedded with siltstones and dark gray shales, and with minor coal seams and limestones. These alternating sequences of sandstone, shale, and siltstone are typical of a delta front environment.

The Naskapi equivalent is a slightly calcareous, micaceous, dark gray shale representing an interdistributary bay to marginal marine and shelf environment. Thick sandstones dominate the Logan Canyon equivalent. These sandstones represent a prograding delta plain sequence of distributary-mouth bars and channel sediments deposited in a nonmarine to marginal-marine environment.

The Upper Cretaceous rocks are equivalent to the Dawson Canyon Formation on the Scotian Shelf. The equivalent formation is composed of gray to brown, slightly calcareous mudstone and represents a major marine transgression. The formation top can be recognized by the appearance of Eocene chalk, limestone, and calcareous shale.

The Cenozoic section consists of the uppermost Dawson Canyon equivalent which is Paleocene in age, Eocene chalk, limestone, and shale, Oligocene to Miocene mudstone and shale and Miocene to Pliocene unconsolidated sand. Few Pleistocene and Holocene cores are available from the shelf. COST B-2 drilled Pleistocene gray and white sands, gravels, and silty clays.

Beneath and seaward of the continental slope, the stratigraphic sequences are poorly documented because of the lack of deep drilling. According to Mattick et al. (1978), the Upper Jurassic to Lower Cretaceous delta sands and shales were deposited in a back-reef environment limited by the narrow, shelf edge fringing stratigraphic reef. They suggest that some sand may have funnelled through channels in the reef and occasionally buried the reef, allowing sand, hemipelagic clay, and reef debris to accumulate on the Mesozoic age paleoslope and rise. The burial of the reef during late Early Cretaceous time allowed more sediment to be deposited in the slope and rise environment. Mattick et al. (1978) suggest that the Upper Cretaceous slope rise deposits were terrigenous muds and turbidites 5,000 - 6,000 m thick which accumulated at rates of 500 - 1,100 m/m.y. Poag (1978) indicates that slope and rise deposits were probably hemipelagic muds and foraminiferal oozes at bathyal depths.

DSDP Leg 11, Site 106 suggests that the slope and rise deposits are silty clays, clayey silts, and mudstones of late middle Miocene and late Miocene age beneath a highly stratified section of Pleistocene terrigenous sands and sandy and silty clays representing deep-water turbidites. Dredges and cores on the continental shelf and slope of North Carolina and within Hudson Canyon indicate that middle Eocene beds are composed of pale yellow to gray, siliceous calcilutites deposited in a bathyal environment (Poag, 1978). Oligocene rocks have been collected on the Hatteras Slope and are calcareous, glauconitic silts, sandstones, and tan-colored chalk representing relatively deep water conditions. On the New Jersey slope, ASP 14 and 15 cored diatomaceous sediments of Miocene age composed of dark, olive-gray to yellow-brown, glauconitic silty clay and sands up to 83 m thick. In Norfolk Canyon ASP 10 and 22 cored middle Miocene diatomaceous sediments up to 110 m thick, of olive-gray to brown clay, sandy clay, and sand without conspicuous glauconite, representing inner shelf to fluvial - marine conditions. On the Hatteras Slope (ASP 7) and within Hudson Canyon are found Pliocene calcareous, clayey sands and sandy clays. On the continental slope AMCOR 6012 and 6021, ASP 7 and 23 encountered Pleistocene gray to dark gray, gassy, silty, and sandy clays up to 300 m thick. These sediments contain planktonic foraminifera and diatoms, middle to outer shelf benthic foraminifera and many dark organic particles. The sediments appear to have formed in locally anoxic depressions on the Pleistocene shelf and subsequently resedimented on the slope. Such sediments are potential gas hydrate hosts.

### Environmental Synopsis

An environmental synopsis in the form of paleolithofacies maps is shown in Figures 10A-G. A marine transgression during latest Jurassic deposited marine sediments upon largely nonmarine sediments of Kimmeridgian age, and a shelf edge fringing carbonate platform was formed. This was followed by a marine regression during Early Cretaceous time as deltaic wedges of sand and mud prograded onto the continental shelf and buried the fringing carbonate platform. A major transgression in Late Cretaceous and early Tertiary time resulted in the deposition of open shelf sandstone, limestone, and calcareous mudstone. However, a major depositional hiatus is observed on the outer shelf close to the Cretaceous - Tertiary boundary. The Cretaceous to Tertiary marine transgression established open marine conditions until the Oligocene; however, during Miocene time marginal marine conditions were reestablished over parts of the continental shelf. The Miocene sands and shales encountered at COST B-2 and other offshore wells are clearly observed on seismic profiles as a seaward prograding clastic wedge marking the shelf edge location. The Cretaceous to Tertiary marine transgression built a broad continental shelf and a gently dipping slope. During the middle and late Tertiary and Quaternary, relative sea level dropped causing the slope to be eroded and exposing older Eocene and Cretaceous rocks. Downslope movement of debris built a sediment wedge having a thickness of up to 3,000 m.

Smith (1980) has demonstrated, from heavy mineral studies, that the provenance of most of the Lower Jurassic and Upper Cretaceous sediments included Triassic rocks to the west from the Province, New England uplands, and Long Island Platform. Thus, the ancient Mesozoic drainage system appears to have had a catchment area similar to that of the present-day Hudson River.

## Lithology

We have chosen specific locations on the continental shelf, slope, and rise in order to illustrate the variations in lithology and physical properties to be expected in these environments. This data is mainly presented in Tables 2 - 4.

### Lower Continental Rise

DSDP Leg 11, Site 105 drilled 633 m of Holocene through Kimmeridgian - Oxfordian sediments, beneath the lower continental rise hills, as located on Figure 5. Lithological information and physical properties are shown in Table 2 and Figure 11.

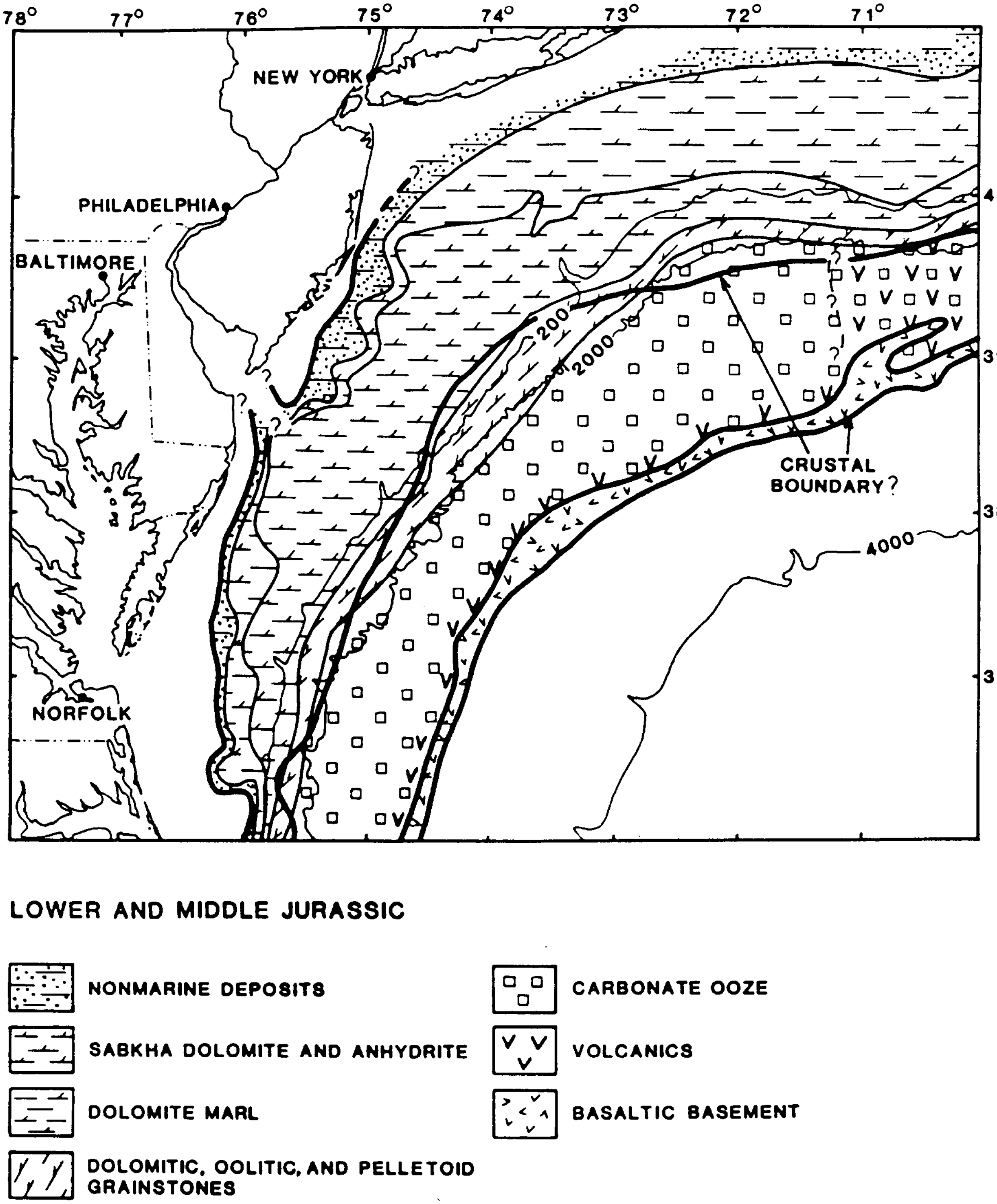



**Figure 10. LITHOFACIES RECONSTRUCTION OF THE CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

**After Libby-French (1984) and Uchupi et al. (1983)**

A Note that the sedimentation is dominated by carbonates with a well developed buildup

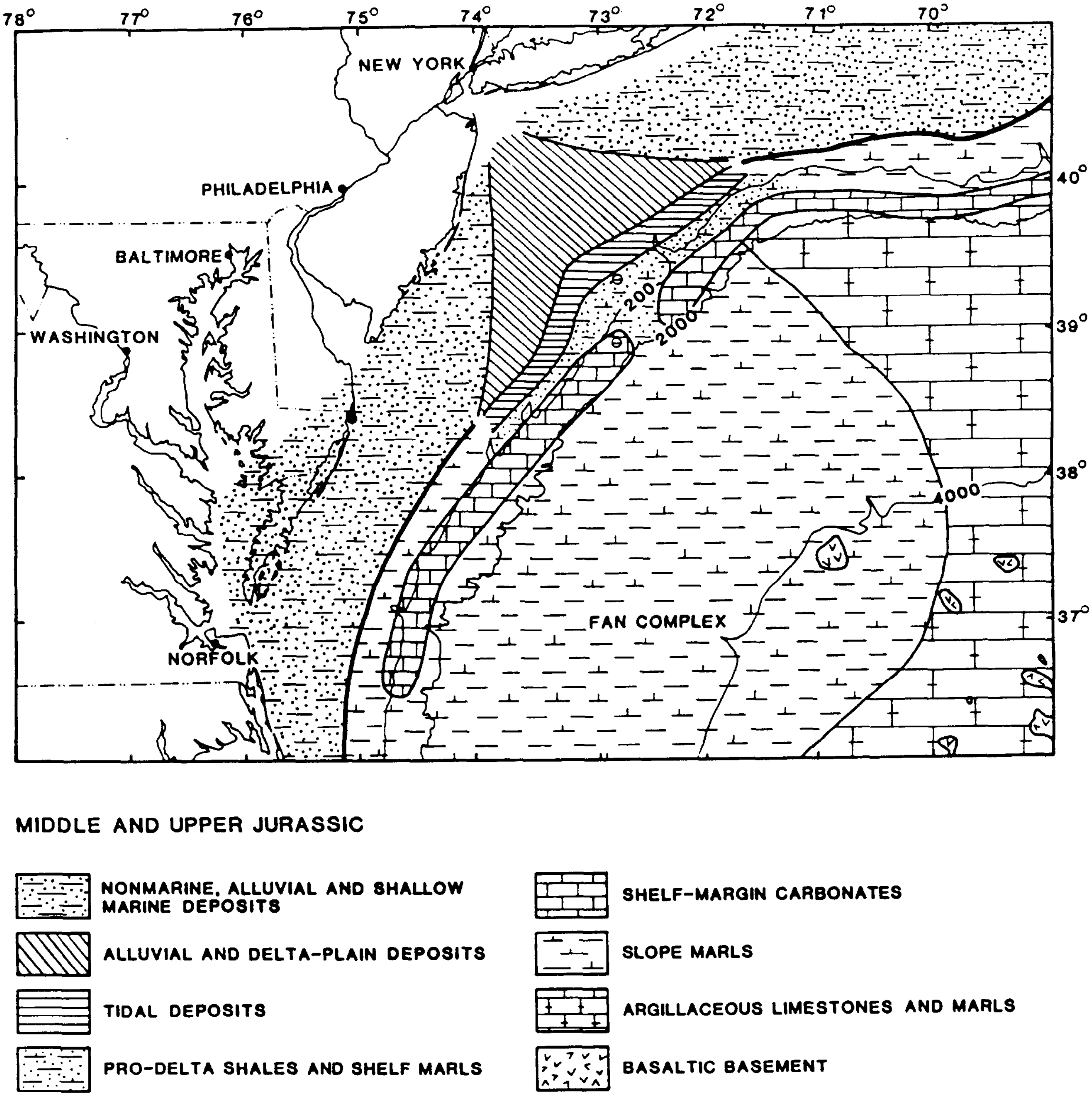
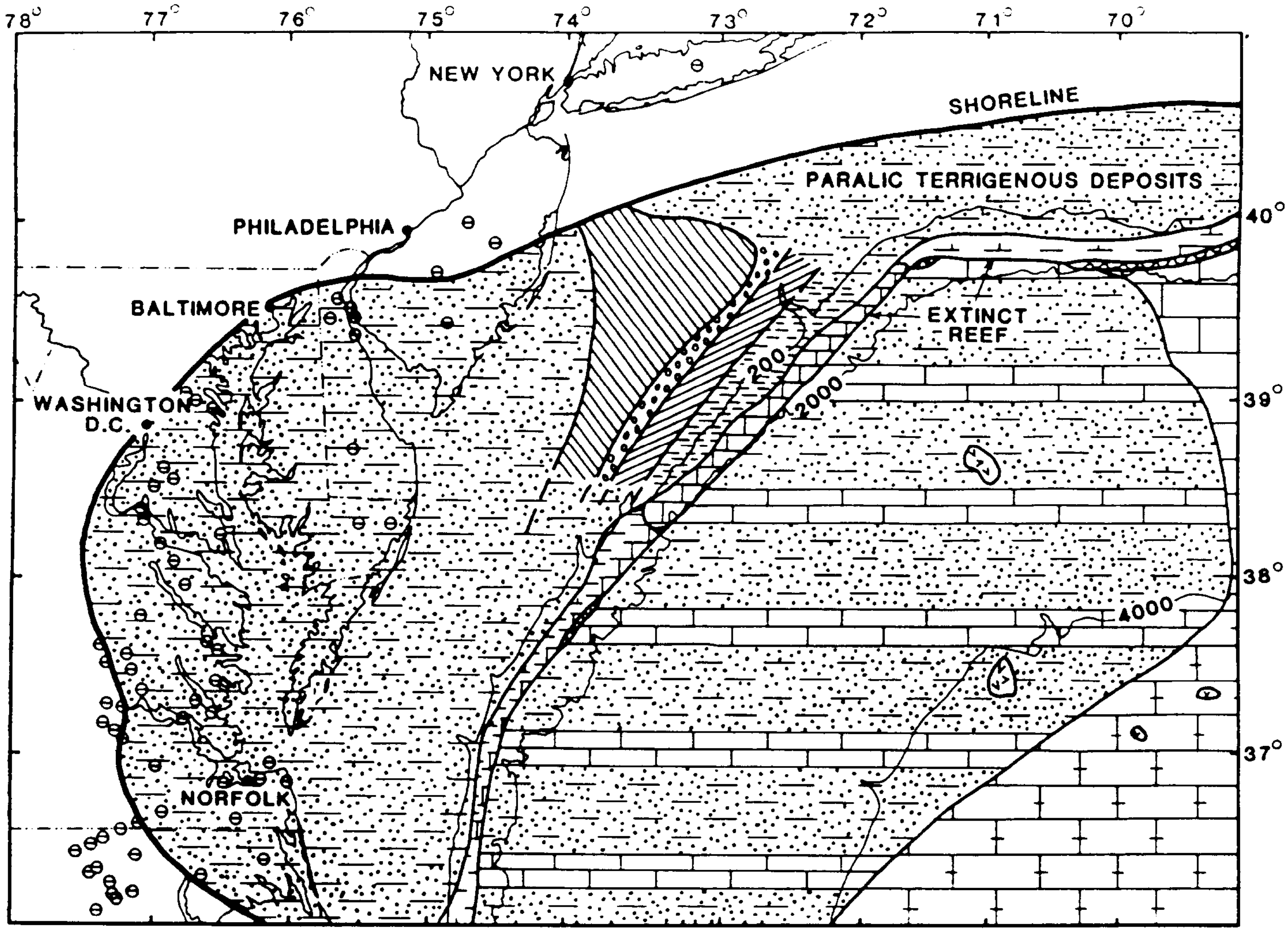



**Figure 10. LITHOFACIES RECONSTRUCTION OF THE CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

**After Libby-French (1984) and Uchupi et al. (1983)**

B. A large deltaic complex originated in area of present day Hudson River. Seaward of the delta are shelf-margin carbonates occasionally breached by shelf clastics. Marls and argillaceous limestones are the dominant slope and rise lithologies.




EARLY LOWER CRETACEOUS

NONMARINE, ALLUVIAL AND SHALLOW MARINE DEPOSITS

ALLUVIAL AND DELTA PLAIN DEPOSITS

CHANNEL AND DISTRIBUTORY-MOUTH BAR DEPOSITS

DELTA FRONT DEPOSITS

PRO-DELTA AND SHELF DEPOSITS

SHELF MARGIN CARBONATES

CLASTICS WITH CARBONATE INTERBEDS

ARGILLACEOUS LIMESTONES AND MARLS

⊖ WELLS DRILLED

**Figure 10. LITHOFACIES RECONSTRUCTION OF THE CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

**After Libby-French (1984) and Uchupi et al. (1983)**

C. The last stage of carbonate build-up at the shelf edge. Carbonate complex breached by the prograding delta.

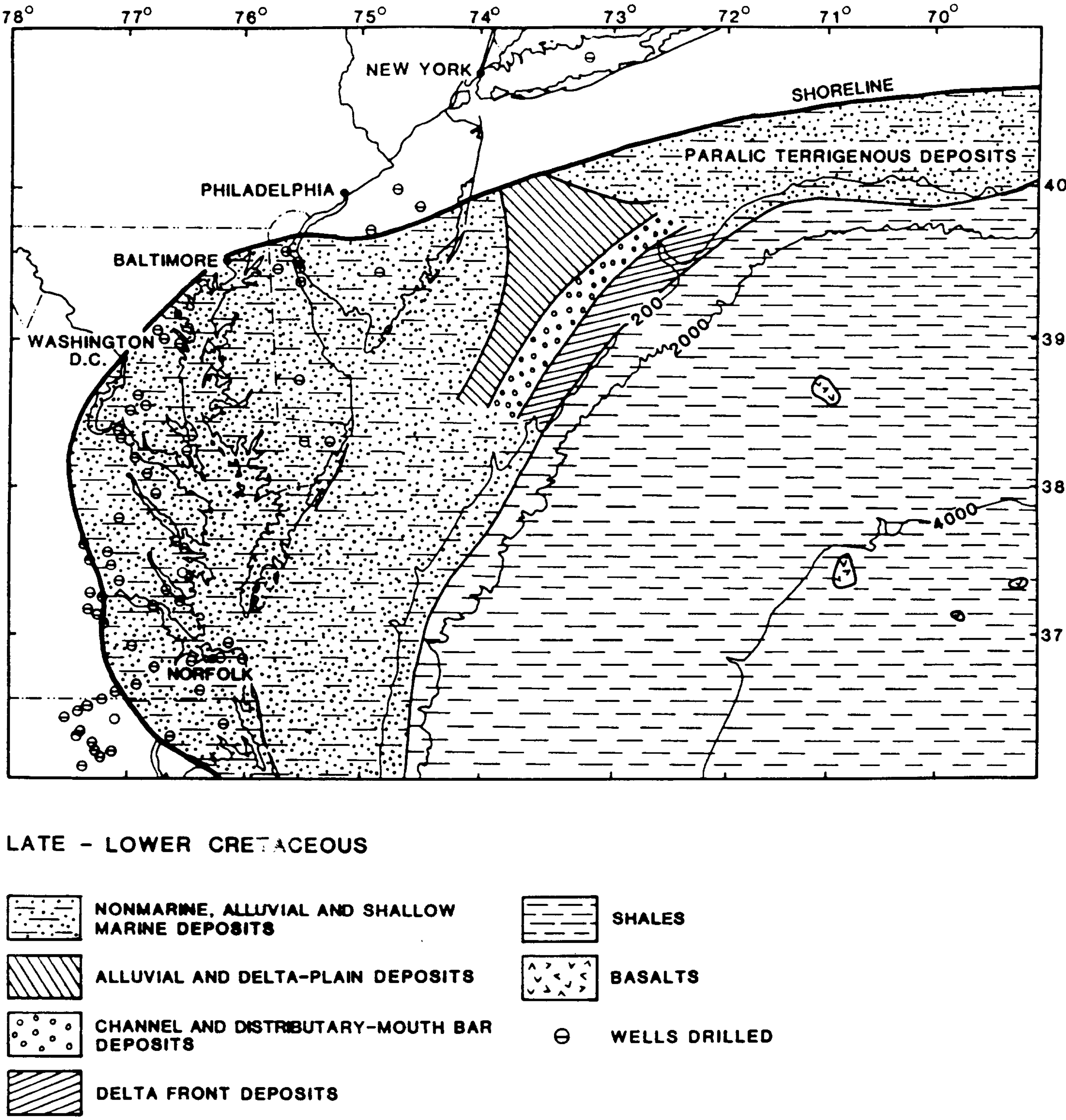
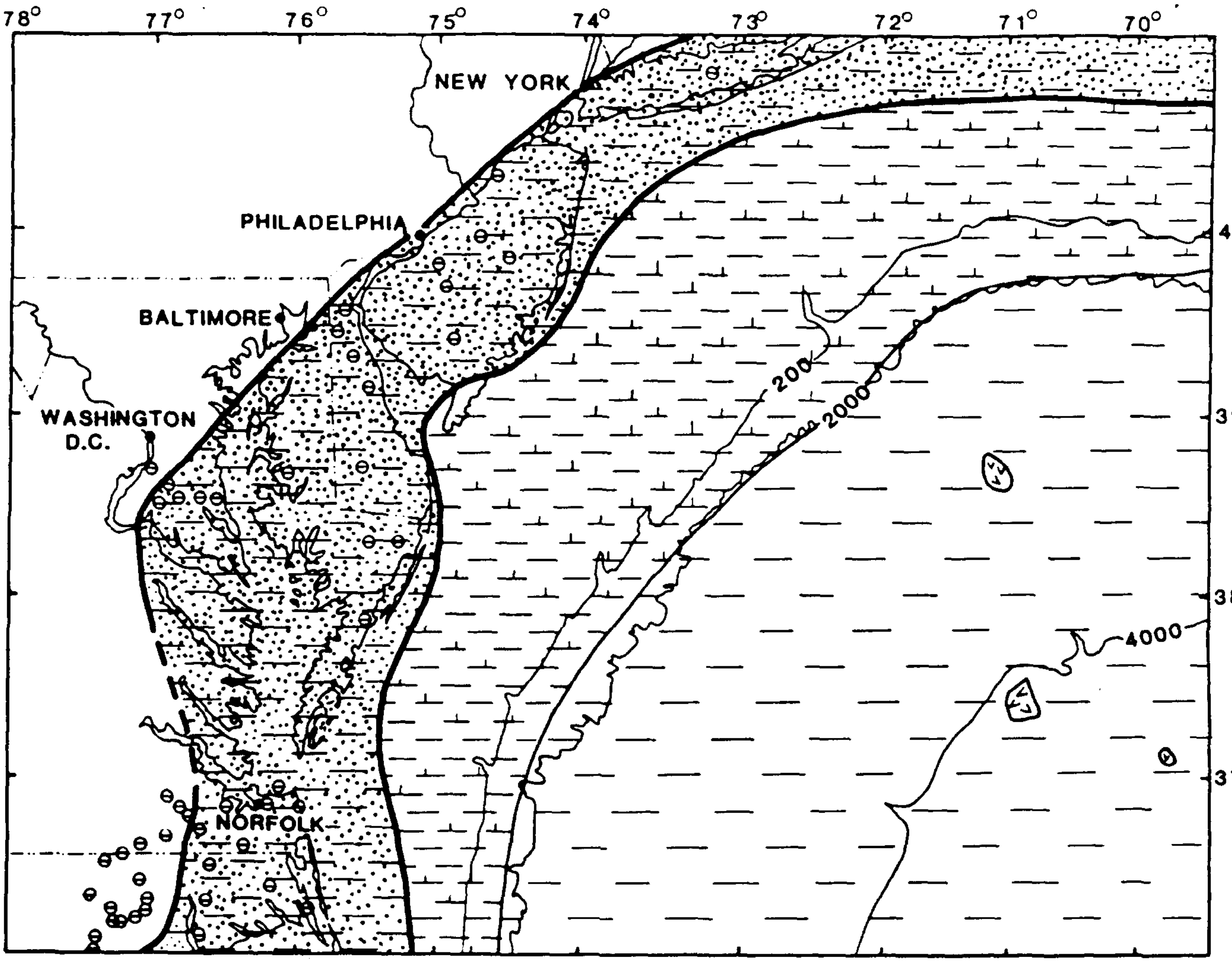



**Figure 10. LITHOFACIES RECONSTRUCTION OF THE CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

**After Libby-French (1984) and Uchupi et al. (1983)**

D. The carbonate shelf-edge complex was buried by prograded deltic facies with distinctive channel and distributary mouth bars and prodelta facies.




UPPER CRETACEOUS

NONMARINE, ALLUVIAL AND SHALLOW MARINE DEPOSITS

SHALLOW-WATER MARLS

SHALES

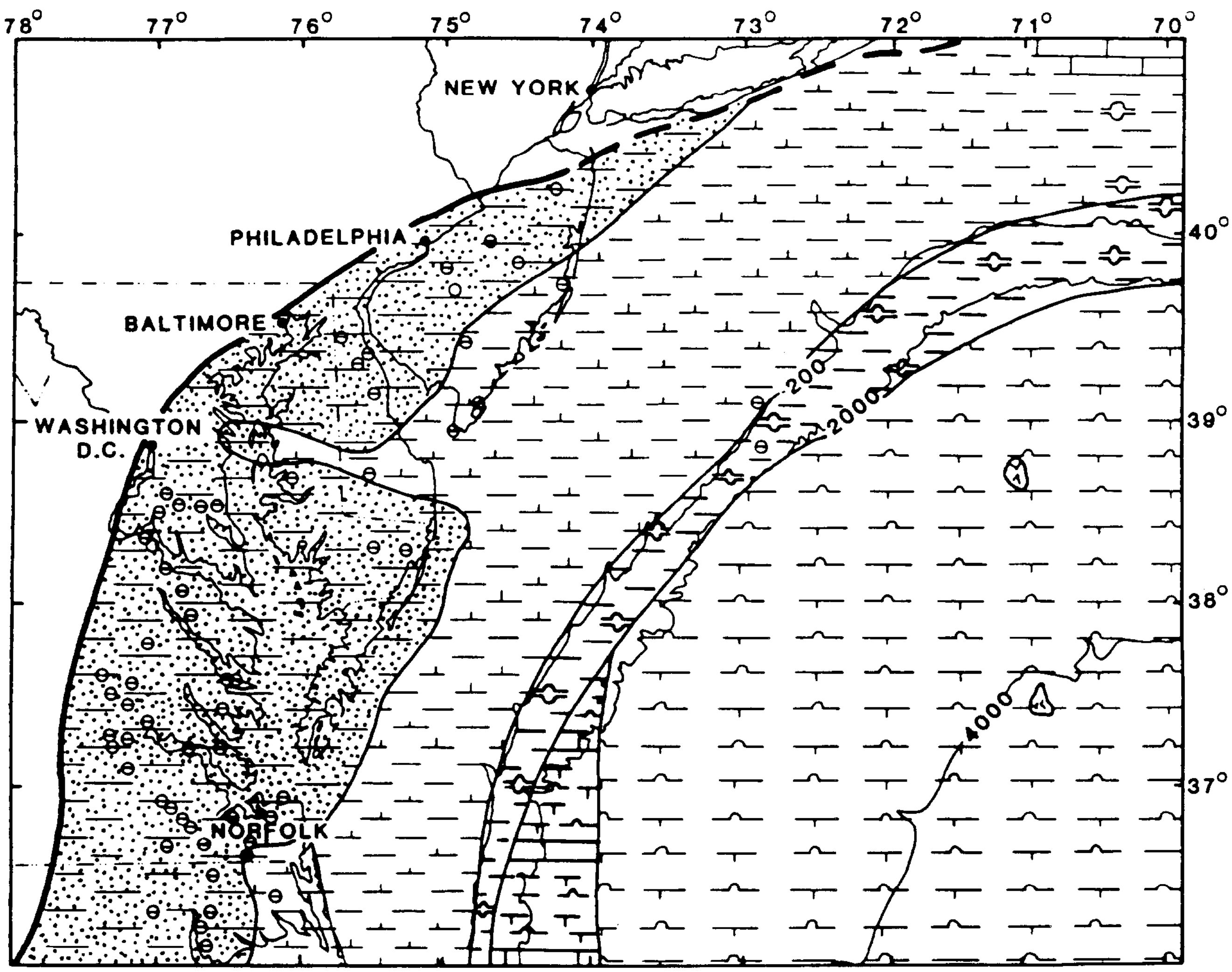
BASALTS

⊖ WELLS DRILLED

**Figure 10. LITHOFACIES RECONSTRUCTION OF THE CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

**After Libby-French (1984) and Uchupi et al. (1983)**

E. Nonmarine and shallow marine clastics laterally graded into shallow water marls on the shelf and deep water shales on the continental slope and rise.




PALEOCENE - OLIGOCENE

NONMARINE AND ALLUVIAL DEPOSITS

SHALLOW-WATER MARLS

DEEP-WATER MARL AND SILICEOUS DEPOSITS

TURBIDITES AND OOZE

⊖ WELLS DRILLED

**Figure 10. LITHOFACIES RECONSTRUCTION OF THE CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

**After Libby-French (1984) and Uchupi et al. (1983)**

F. Tertiary cycle of marine transgression and regression resulted in turbidite deposition in deep water.

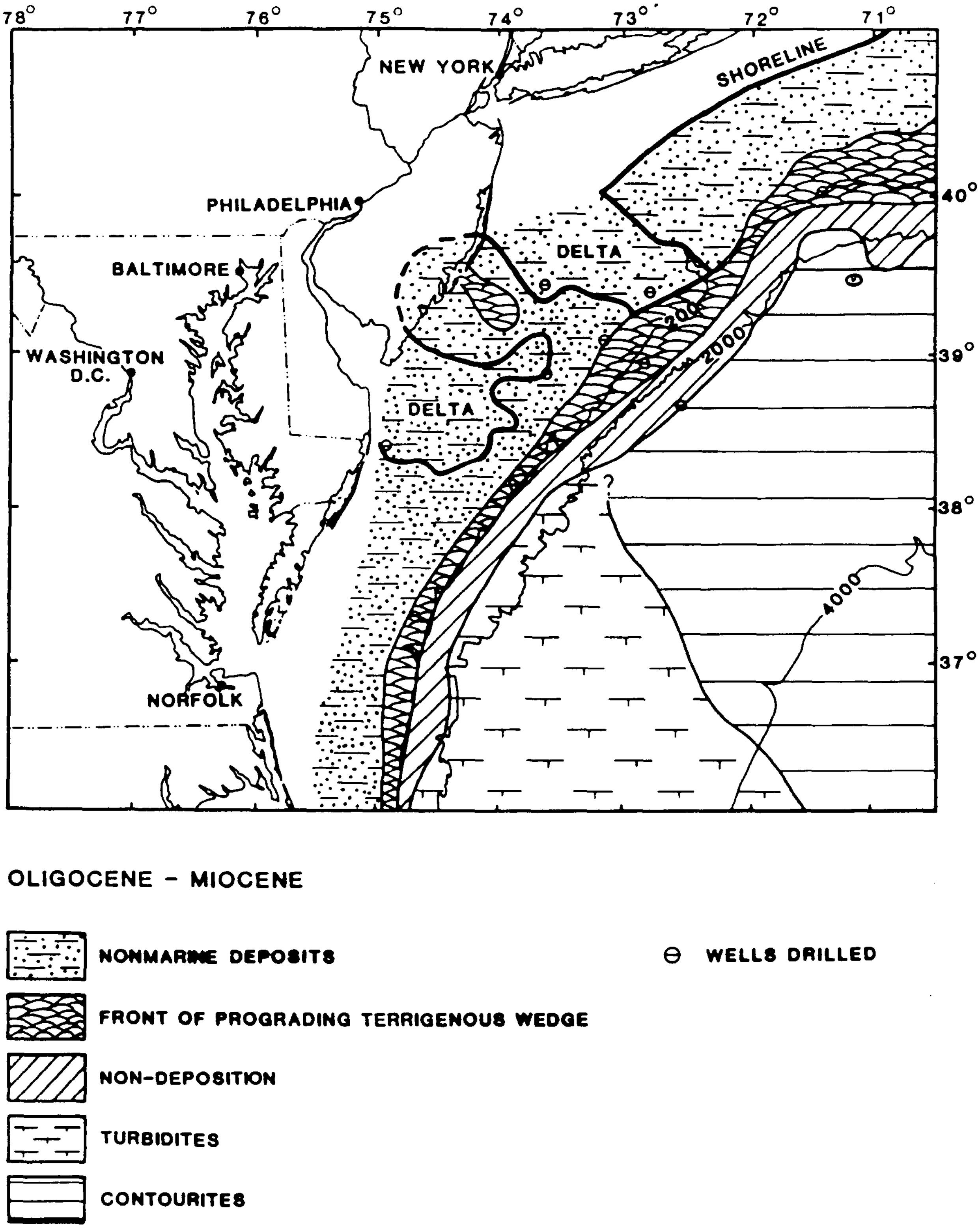



**Figure 10. LITHOFACIES RECONSTRUCTION OF THE CONTINENTAL MARGIN IN VICINITY OF BALTIMORE CANYON TROUGH**

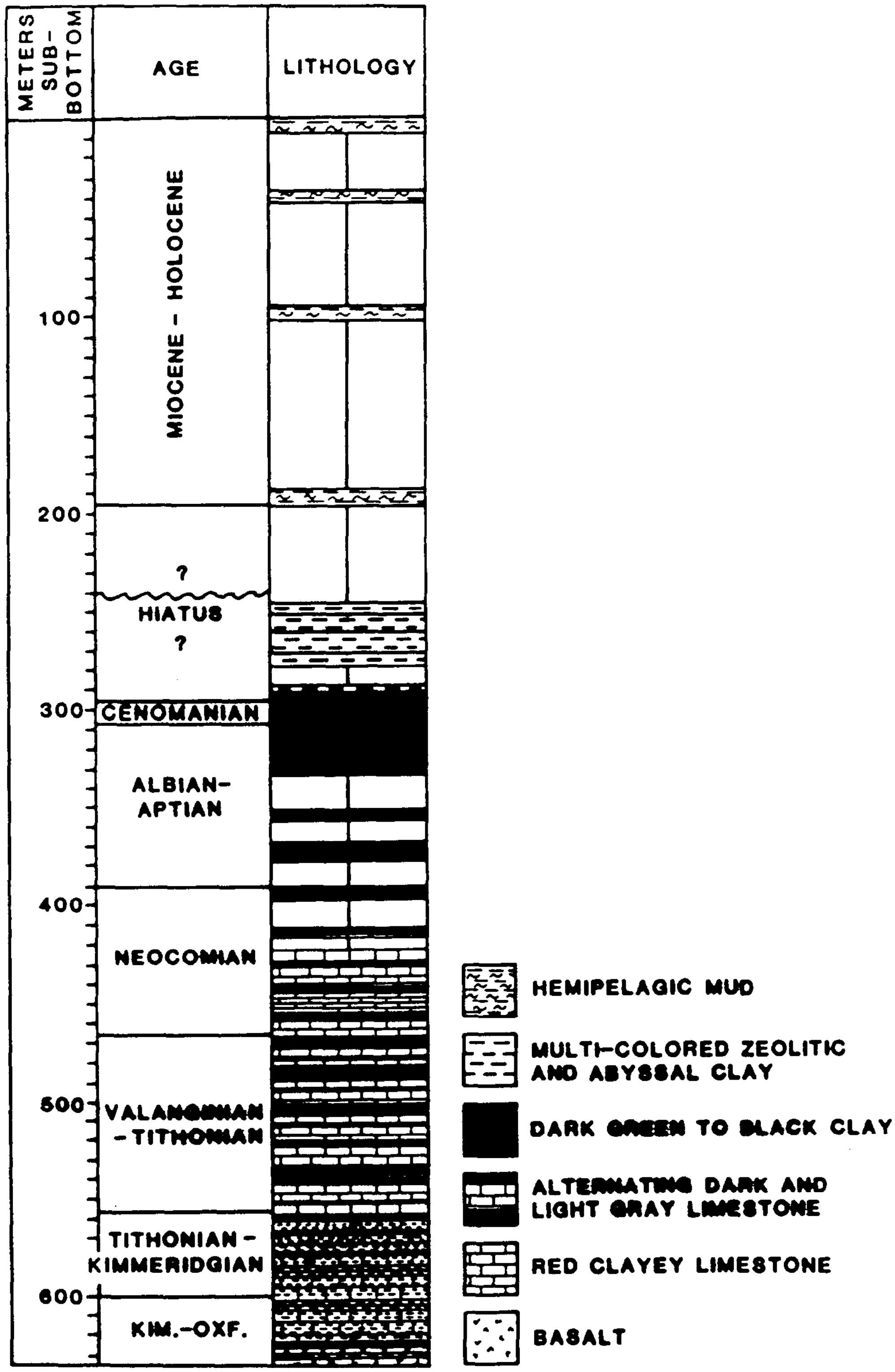
**After Libby-French (1984) and Uchupi et al. (1983)**

G. Lowered sea level led to further progradation on deltaic wedges. Occasionally shelf was exposed to erosion providing detritus for deep water turbidites. The interaction of the Western Boundary Undercurrent and the Gulf Stream redistributed some sediments and

TABLE 2

LITHOLOGY AND PHYSICAL PROPERTIES FOR DSDP LEG 11, SITE 105

| Age | Depth m | Lithology | Porosity wt % | Porosity vol % | Wet Bulk Density $g/cm^3$ | Sonic Velocity km/sec |
|---|---|---|---|---|---|---|
| Pleistocene | 32 | Dark, greenish-gray terrigenous sand | 38 | 57 | 1.80 | nd |
| | 33 | Gray, greenish, yellow hemipelagic mud | 38 | 62 | 1.60 | nd |
| | 35 | Olive gray hemipelagic mud | 39 | 58 | 1.70 | nd |
| Early Pliocene | 92 | Greenish-gray hemipelagic mud | 38 | 60 | 1.75 | 1.54 |
| | 94 | Greenish-gray hemipelagic mud | 37 | 57 | 1.78 | 1.54 |
| Late Miocene? | 185 | Greenish-gray silty clay | 40 | 63 | 1.60 | 1.53 |
| | 188 | Mottled silty clay | 37 | 60 | 1.75 | 1.53 |
| | 193 | Mottled silty clay | 37 | 60 | 1.75 | 1.62 |
| Tertiary? | 242 | Mottled silty clay | 34 | 50 | 1.70 | 1.62 |
| | 245 | Mottled silty clay | 34 | 48 | 1.75 | 1.65 |
| Not Determined | 260 | Light brown hemipelagic clay | 36 | 55 | 1.60 | nd |
| | 266 | Light brown silty clay | 29 | 53 | 1.80 | nd |
| | 274 | Silty clay, semi-plastic, firm | 27 | 50 | 1.80 | 1.68 |
| Cenomanian | 294 | Silty clay, semi-plastic, firm | 24 | 60 | 1.78 | nd |
| | 304 | Dark brown silty clay | 40 | 60 | 1.75 | 1.66 |
| Cenomanian-Albian | 309 | Black silty clay, semi-plastic, firm | 24 | 50 | 1.72 | nd |
| | 322 | Black, zeolitic clay | 30 | 48 | 1.75 | 1.55 |
| Albian | 355 | Black clay | 28 | 55 | 1.70 | nd |
| | 375 | Black clay | 28 | 55 | 1.60 | nd |
| Aptian-Barremian | 392 | Black clay | 27 | 53 | 1.62 | nd |
| | 396 | Black clay | 27 | 53 | 1.62 | nd |
| Barremian-Hauterivian | 404 | Black clay | 29 | 58 | 1.50 | nd |
| | 408 | Clayey limestone | 29 | 59 | 1.50 | nd |
| | 430 | Chalky limestone | 25 | 50 | 1.80 | 1.58 |
| | 457 | Chalky limestone | 29 | 55 | 1.55 | nd |
| Tithonian | 475 | Chalky limestone | 21 | 40 | 1.90 | nd |
| | 484 | Chalky limestone | 21 | 40 | 1.85 | nd |
| | 511 | Chalky limestone | 22 | 43 | 1.60 | nd |
| Kimmeridgian-Oxfordian | 559 | Chalky limestone | 22 | 42 | 1.50 | nd |
| | 564 | Chalky limestone | 26 | 48 | 1.60 | nd |




**SITE 105**

**Figure 11. LITHOSTRATIGRAPHIC SUMMARY FOR DSDP LEG 11, SITE 105 U.S. ATLANTIC MARGIN, LOWER CONTINENTAL RISE, AT 34°53'N, 69°10.4'W, IN 5250m WATER DEPTH**

DSDP Leg 11, Site 106 drilled 1,015 m of Eocene to Holocene sediments on the lower continental rise to the north of Site 105 (see Figure 5), without substantial core recovery. Data for the cored intervals are shown in Table 3 and Figure 12.

### Upper Continental Rise

DSDP Leg 11, Site 107 drilled 78 m, with very poor core recovery, into Pleistocene sediments on the rise between South Toms and Berkeley Canyons (Figure 5). Pertinent data are shown in Table 4.

### Continental Slope

DSDP Leg 11, Site 108 drilled 209 m, with poor core recovery, on the lower continental slope northwest of Site 107 (Figure 5). Middle Eocene sediments, composed of light gray, siliceous chalk, were recovered at less than 75 m depth. No physical properties were measured.

COST B-3 well was drilled to 3,990 m in the middle slope (Figure 1), recovering Kimmeridgian through Miocene sediments. Younger sediments were present but not recovered. Lithologic and physical properties data are shown in Figure 13.

### Continental Shelf

COST B-2 well was drilled to 4,77[illegible] through Barremian to Pleistocene sediments near the outer shelf (Figure [illegible] Pertinent data are shown in graphical form in Figure 14.

## Basin Development

The development of the Baltimore Canyon Trough and sedimentation on the associated continental slope and rise are intimately associated with subsidence of the western Atlantic Continental Margin following continent separation. The development of basins as a consequence of thermal subsidence in such settings has been extensively investigated in a large number of publications: e.g. Sleep, 1971; Foucher and Le Pichon, 1972; Falvey, 1974; Bally, 1976; Sleep and Snell, 1976; Parsons and Sclater, 1977; McKenzie, 1978; Pitman, 1978; Steckler and Watts, 1978; Watts and Steckler, 1979; Keen, 1979; Jarvis and McKenzie, 1980; Royden et al., 1980; Royden and Keen, 1980; Sclater and Christie, 1980; Le Pichon and Sibuet, 1981; Steckler, 1981; Karner and Watts, 1982; Watts, 1982; Watts and Thorne, 1984. Thermal evolution models dealing specifically with the Baltimore Canyon Trough have been developed by Angevine and Tucholke, 1981; Watts, 1981; Sawyer et al., 1982. We have not attempted another thermal model for the Baltimore Canyon Trough. The consistency of previous models suggests that such an effort would be redundant.

TABLE 3

LITHOLOGY AND PHYSICAL PROPERTIES FOR DSDP LEG 11, SITE 106

| Age | Depth m | Lithology | Porosity wt % | Wet-Bulk Density g/cm³ |
|---|---|---|---|---|
| Late Pleistocene | 5 | Soft, plastic, hemipelagic mud | 42 | 1.5 |
| | 45 | Soft, plastic, hemipelagic mud | 34 | 1.7 |
| | 115 | Brown, hemipelagic mud | 30 | 1.8 |
| Early Pleistocene | 265 | Brown, hemipelagic mud | 29 | 1.7 |
| | 345 | Firm, plastic, hemipelagic mud | 30 | 1.6 |

Notes:
1. Below 366 m Pliocene and Miocene muds are very firm and indurated
2. Miocene mudstone cored at 935 m very hard, requiring diamond-saw cutting
3. At 1,012 m silicified claystone and siderite prevented further drilling
4. No sonic velocity measurements were made at Site 106

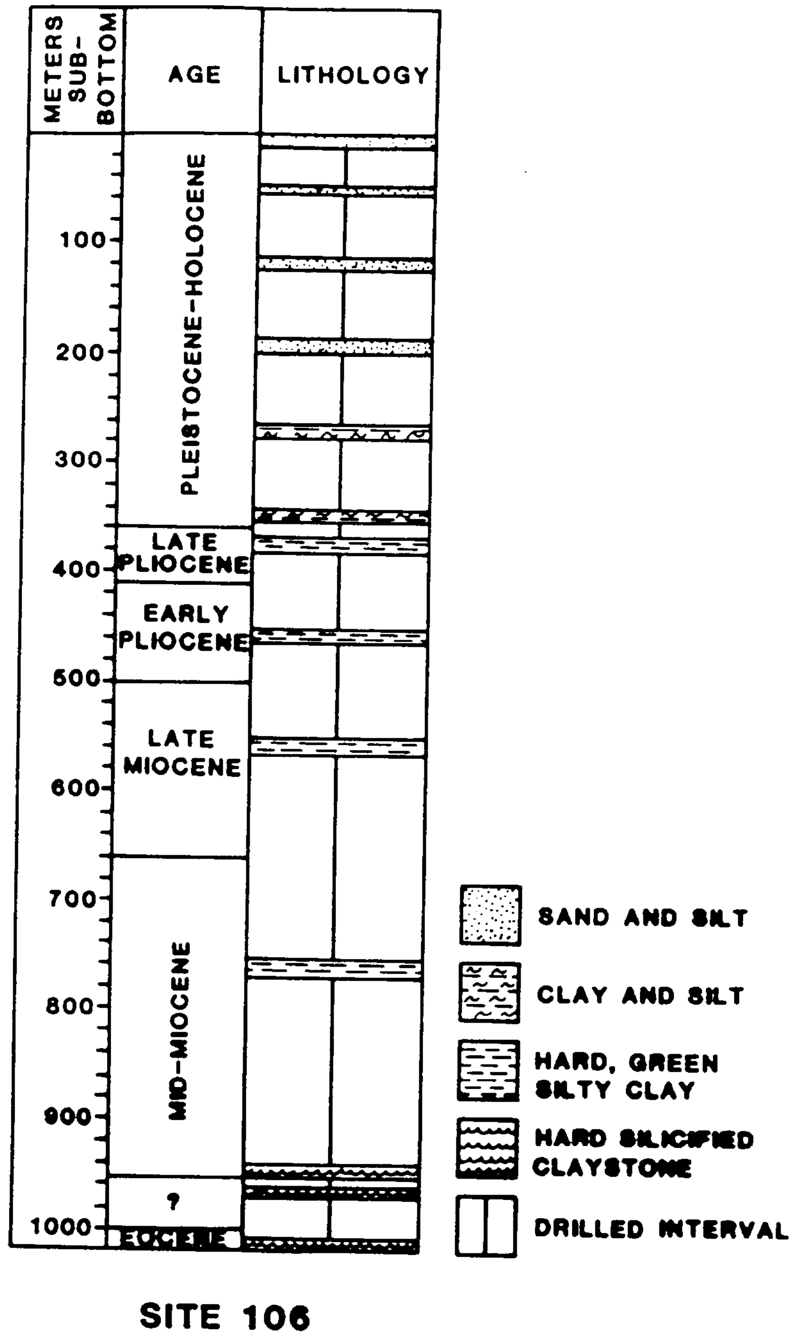



**Figure 12. LITHOSTRATIGRAPHIC SUMMARY FOR DSDP LEG 11, SITE 106, U.S. ATLANTIC MARGIN, LOWER CONTINENTAL RISE, AT 36°26'N, 69°27.7'W, IN 4500m WATER DEPTH**

TABLE 4

LITHOLOGY FOR DSDP LEG 11, SITES 107 AND 108

| Site | Age | Depth m | Lithology |
|---|---|---|---|
| 107 | Pleistocene | 57 - 62<br>75 - 78 | Soft, gray hemipelagic mud<br>Dark gray hemipelagic mud |
| 108 | Middle Eocene | 39 - 75 | Indurated, greenish gray siliceous nannofossil-foraminiferal ooze, moderately to intensely burrowed, terrigenous components rare |

FIGURE 13. Lithilogic Descriptions and Physical Properties Measurements at Cost B-3 Well, U.S. Atlantic Margin, is located in the pocket at the end of the report.

FIGURE 14. Lithologic Descriptions and Physical Properties Measurements at Cost B-2 Well, U.S. Atlantic Ridge, is located in the pocket at the end of the report.

## Thermal Model

The following is a brief discussion on the thermal model developed by Sawyer et al., 1982.

A two-dimensional finite difference numerical scheme was used to simulate the thermal evolution of the Baltimore Canyon Trough and the associated regions of the continental slope and rise. This model provided a time - temperature history for the basin as indicated in Figure 15 for the slope region of the COST B-3 well. The relation of the time and temperature curves to hydrocarbon maturation can be determined in several different ways. In Figure 15 the shaded areas are bounded by isomaturity contours representing levels of organic matter maturity. In effect, such contours are the organic matter equivalent of classical metamorphic isograds, and have been discussed by Waples (1980) and Royden et al. (1980).

The solid curves indicate the temperature history of sediments deposited from Late Triassic through Mid-Cretaceous. Younger sediments are excluded because they are obviously immature with regard to hydrocarbon generation. In fact, even the Cretaceous sediments appear to be immature with regard to oil generation. The maturity values (C) between 10 and 16 correspond to vitrinite reflectance values between approximately 0.65 and 1.3 and thus, represent the so-called "oil window". At higher C values the sediments are mature with regard to condensate and wet gas generation and finally to dry gas (methane) production.

Note that Figure 15 indicates that presently the Lower Jurassic section would be mature with regard to dry gas production beneath the upper slope region, and has been so since about 130 m.y. The organic matter in this section is dominated by terrestrial material, so that throughout most of the burial history since approximately 170 m.y. this section has been gas prone. With regard to the present level of maturation, much of the Jurassic section is mature with regard to oil generation from marine organic matter. However, the Jurassic section in the vicinity of the COST B-3 well is landward of the Jurassic paleoshelf and consequently the organic matter is probably dominated by terrestrial (Type III) types. Thus, we conclude that the complete Jurassic section in this area of the slope would produce principally gas with minor hydrocarbon liquids.

The maturity region with $C < 10$ in Figure 15 is shown as immature with regard to oil generation but nonetheless, the Early Cretaceous section should have the potential for generating a small volume of immature gas or even immature early oil. Figure 16 shows the predicted contours of thermal maturity in the Baltimore Canyon Trough at the present time along the USGS seismic line 25. Note that the predicted region for thermally mature (with respect to oil generation) sediments extends from beneath the shelf to the continental rise. The possibility that the deeper sediments (greater than 5,000 m of burial) have generated liquid hydrocarbons beneath the slope is greater than beneath the shelf because we believe that the slope sediments may be richer in organic matter and also may contain more marine Type I organic matter. Also, the slope and rise sections are undermature with regard to dry gas generation and the overmature realm cannot therefore contribute methane for possible trapping in a gas hydrate system. Extension of Figure 16 into the region of the continental rise suggests that the deeper sediments may be marginally mature with regard to hydrocarbon generation. It is also important

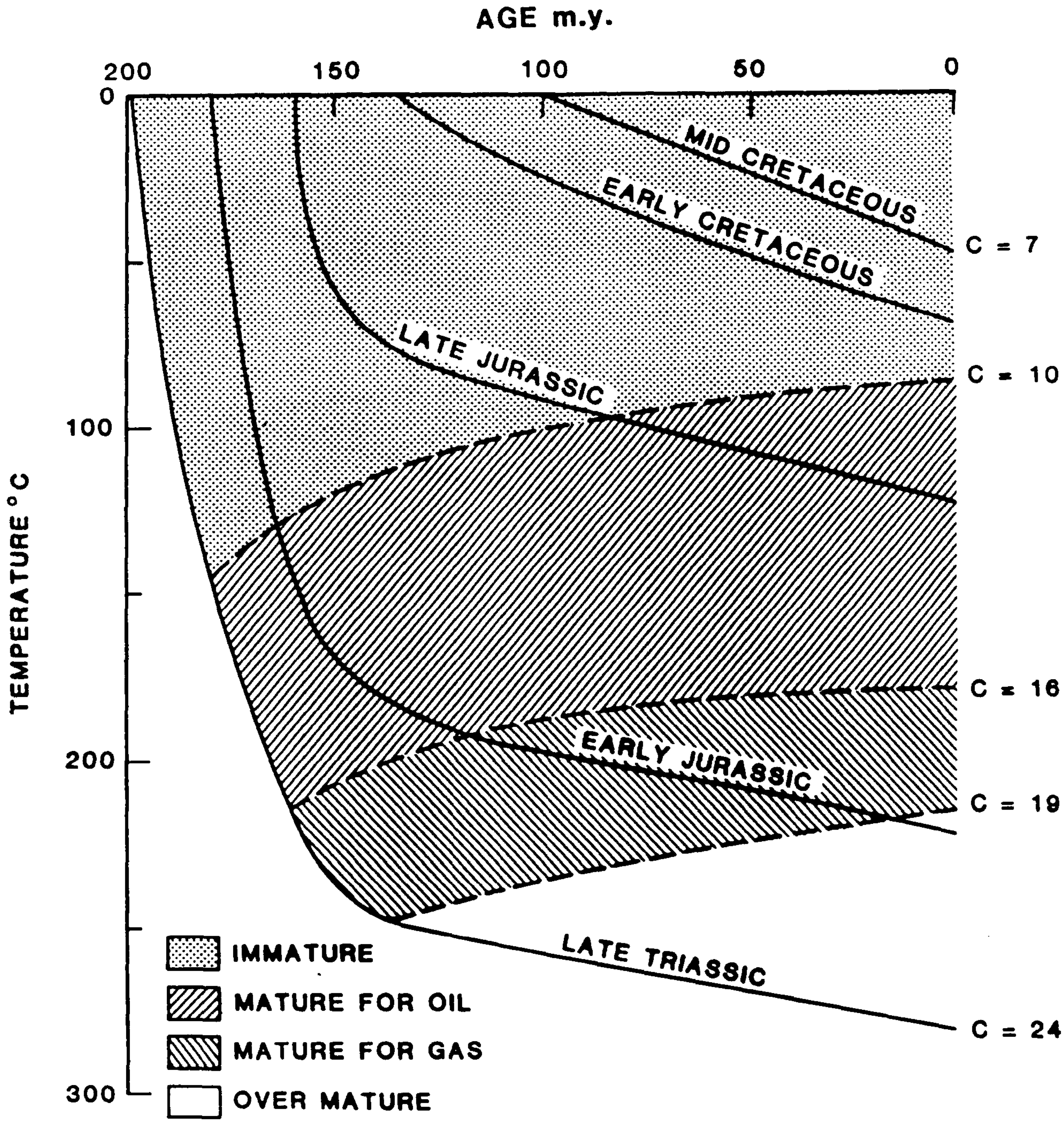



**Figure 15. TEMPERATURE - TIME HISTORY OF THE COST B-3 WELL ON THE CONTINENTAL SLOPE**

**After Sawyer et al. (1982)**

The solid curves show the thermal history for sediments deposited at 200, 180, 160, 136, and 100 m.y. The shaded areas represent the regions for immature, mature, and overmature sediment based upon the iso-maturity (C) contours of Royden et al. (1980).

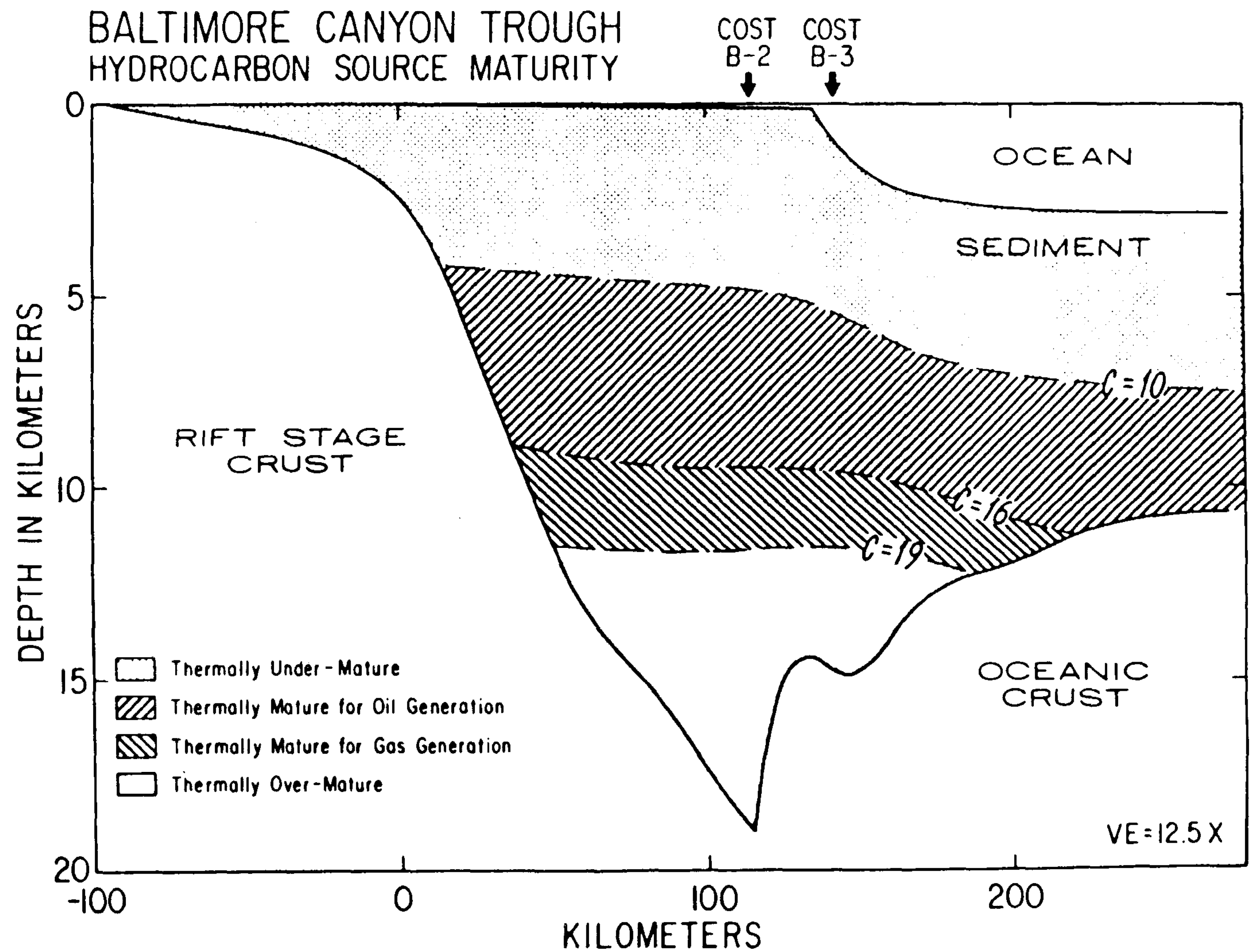



**Figure 16. CONTOURS OF THERMAL MATURITY (C) FOR BALTIMORE CANYON TROUGH AND ASSOCIATED CONTINENTAL SLOPE AND RISE**

**After Sawyer et al. (1982)**

Stratigraphic data are from COST B-2, COST B-3 and USGS seismic line 25. Shaded areas are regions of immature, mature, and overmature sediment.

to note that the decreased sedimentation rate over parts of the continental rise may result in the selective concentration of organic matter in the rise sediments, consequently increasing the likelihood for methane production beneath the C = 10 isomaturity surface. The continental rise sediments thin to less than 5,000 m in thickness at approximately 3,500 m water depth, and at this point the temperature distribution is inadequate to generate hydrocarbons by thermal degradation.

## Conclusions

This discussion suggests the following conclusions:

1. Although greater than 15,000 m of sediment accumulated in the Baltimore Canyon Trough beneath the present-day continental shelf, exploration has been disappointing even though the sediments from approximately 5,000 - 10,000 m depth are mature for hydrocarbon generation. This suggests that the lack of appropriate source lithologies may be critical in determining the hydrocarbon potential of the basin.

2. Extension of the thermal profile to the continental slope rise region indicates that the deeper lithologies may be mature for oil and gas generation. The prospect for source beds with more generating potential beneath the slope is brighter if it is assumed that more marine organic matter has accumulated in this region.

3. The deeper lithologies beneath the rise may have a better gas potential, due to the reemergence of terrestrially dominated organic matter. The critical factor will be the amount of organic matter preserved in this environment.

4. With regard to gas reservoirs beneath hydrate seals, it appears that the thermal conditions beneath the slope and the rise to 3,500 m water depth would be conducive to the thermal production of methane, which might rise vertically and be trapped. It is interesting to note that BSRs have not been located at greater than approximately 3,500 m water depth, which may relate to the lack of thermogenic methane.

5. Assuming that thermogenic methane has been generated beneath the continental rise, the probability that the lithologies are dominantly hemipelagic clays will strictly limit the migration paths for gas to vertical or subvertical directions. If such migration occurs, gas may be trapped beneath a hydrate seal, if one is present.

## PART II

## OCCURRENCES AND STABILITY OF GAS HYDRATES

### Seismic Evidence

The recognition of the continental slope and rise in the vicinity of the Baltimore Canyon Trough as potential sites for gas hydrates and related gas reservoirs is based entirely on the recognition of bottom simulating reflectors (BSRs) on seismic profiles (Tucholke et al., 1977). BSRs have been recognized on seismic lines from Lamont-Doherty Geological Observatory (LDGO) and U.S. Geological Survey (USGS), particularly those profiles across the continental margin.

Tucholke et al. (1977) have recognized three classes of BSRs depending upon the reflection strength and continuity (see Krason and Ridley, 1985, for a further discussion). Class 1 reflectors are strong returns with lateral continuity, Class 2 reflectors are also strong returns but laterally discontinuous, and Class 3 reflectors are weaker and laterally discontinuous and diffuse. Figure 17 indicates the areal distribution of the BSR classes in this region. The strongest reflectors (Class 1) are found between Wilmington and Hudson Canyons in the region of the continental rise between 2,500 m and 3,500 m water depth and are flanked to the northeast and southwest by more diffuse Class 2 and 3 reflectors on the continental rise. The probability exists that shallower BSRs exist but have not been identified by Tucholke et al. (1977). These authors also limit the areal extent of the BSR to areas covered by at least 2,500 m of water in the Blake Outer Ridge region, but Paull and Dillon (1981) have demonstrated that the BSR can be observed beneath ocean depths as shallow as 750 m.

Figure 18 indicates the position of the BSR on a profile across the continental rise shown in Figure 15. The BSR can be recognized because the sedimentary bedding reflectors dip either slightly landward or are horizontal, whereas the BSR following the sea floor topography dips gently seaward. Seaward the BSR becomes diffuse but also the bedding reflectors dip eastward so the nonconformable relationship is absent.

As noted by Tucholke et al. (1977), the geometric arrangement of bedding and BSR is optimal for gas trapping if lateral gas migration is an important process. Landward dipping bedding causes an eastward gas migration which is then trapped by the eastward dipping hydrate sea. This may be an important mechanism whereby a gas reservoir can develop beneath a hydrate seal, although it is not obvious that it is an important mechanism for hydrate formation.

Unlike the Class 1 BSR at the Blake Outer Ridge, which acts as a structural seal partly by virtue of the anticlinal shape of the ridge, the

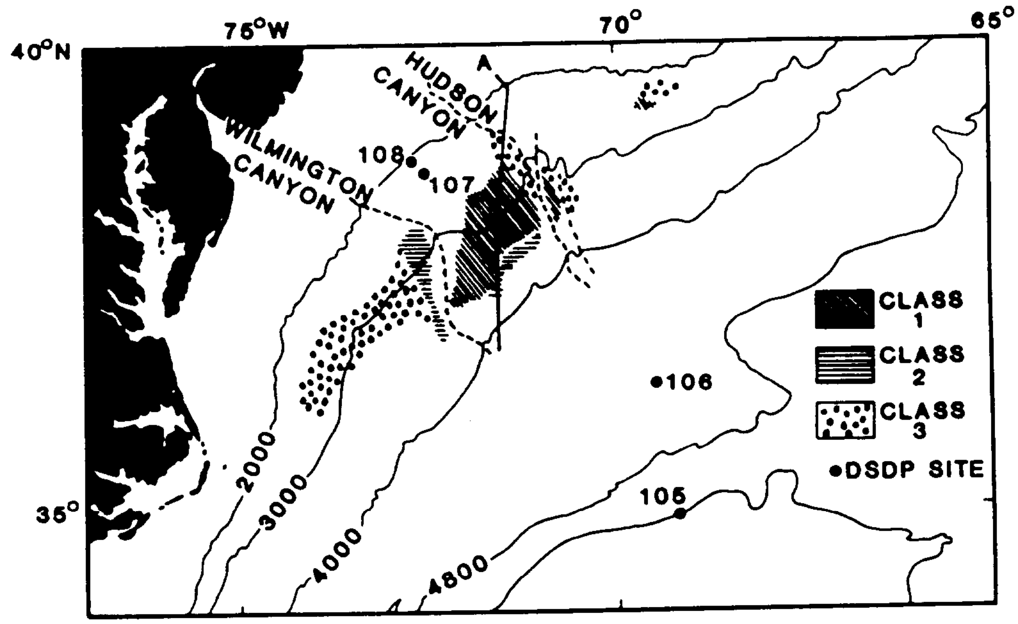



**Figure 17. DISTRIBUTION OF BOTTOM SIMULATING REFLECTORS IN THE REGION OF THE BALTIMORE CANYON TROUGH**

**After Tucholke et al. (1977)**

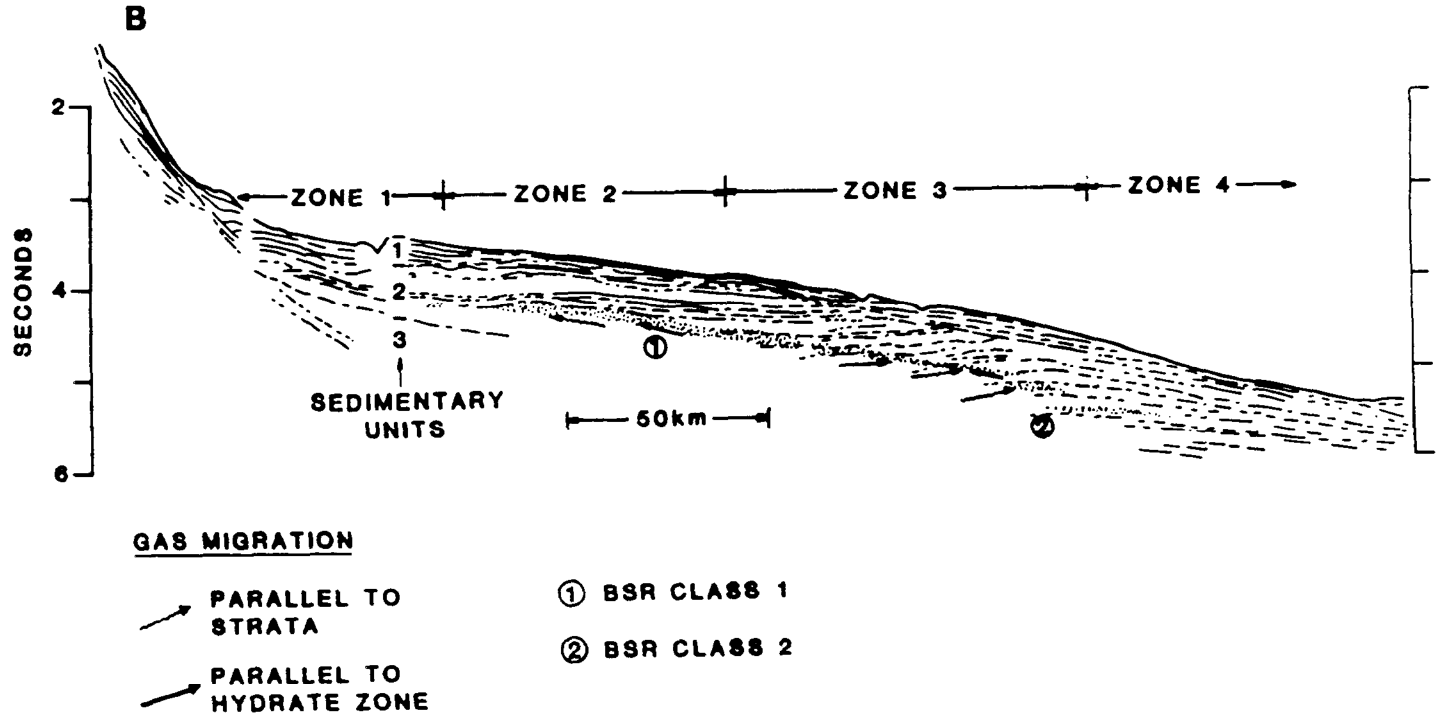



**Figure 18. INTERPRETATION OF SEISMIC PROFILE B, U.S. ATLANTIC MARGIN RISE REGION, OFFSHORE NEW JERSEY**

**After Tucholke et al. (1977)**

continental rise BSR appears to be a flat and eastward dipping horizon which mimics the subdued rise topography. Thus, the hydrate zone may not be an efficient seal in this locality. Leakage of gas might be expected in those areas where the force of eastward gas migration is unable to prevent the gradual loss of gas by movement updip along the base of the gas hydrate zone.

Figure 19 represents depth to the BSR from the sea floor as a function of water depth, and shows the approximately positive correlation observed for the Blake Outer Ridge (Tucholke et al., 1977). These authors reference the data to a geothermal gradient of 3.95°/100 m. Also shown is a 3.6°/100 m gradient which is also appropriate for the Blake Outer Ridge. Which, if either, of these values is a useful reference gradient for the rise in this region is unknown. Gradients measured through the shelf and upper continental slope at COST B-2 and COST B-3 indicate an anomalously low gradient (2.3°/100 m) but the thermal profiles may be out of equilibrium in these areas of rapid sedimentation. On the lower slope and rise, where sedimentation rates were lower, a closer approach to the steady-state gradient is expected. Assuming the continental rise lithologies are principally hemipelagic muds and clays, subjected to the present-day heat flow through basement of 1.1 HFU, then the equilibrium temperature gradient would be about 3.7°/100 m. Given that the position of the gradient curves in Figure 19 is particularly sensitive to the gradient value chosen, which is not well constrained here, it would seem premature to infer gas hydrate composition from such a diagram. Certainly a multitude of potential factors, including local variations in lithology and compaction (which determine thermal conductivity), transient thermal effects due to local erosion and deposition, and slight variations in gas composition may contribute to the scatter of depth values observed in Figure 19.

## Sedimentary Environment on the Continental Slope and Rise

A number of studies have indicated the inherent instability of sediment on the continental slope and rise adjoining the Baltimore Canyon Trough region (Uchupi, 1967; McGregor and Bennet, 1977; Knebel and Carson, 1979; McGregor, 1979, 1982; Schlee et al., 1979). The two processes involved here are sediment transport into deep water by turbidity currents down submarine canyons and mass slumping and sliding on the slope. Both of these processes were probably initiated during Pleistocene low stands of sea level when the slope was subjected to intense subaerial erosion and when increased forces acted on slope sediments due to the lowered wave base. However, the exact ages of observed sediment slides is unknown. Small-scale slumping is probably an active process but large-scale block sliding was probably most prevalent during the Pleistocene (see Robb and Twitchell, in Schlee et al., 1979).

The sizes of slumped blocks on the slope may be on the order of several kilometers, implying a depth of at least a hundred meters for the larger blocks (Knebel and Carson, 1979). McGregor (1982) has documented mass sediment movements and associated erosional scarps with relief of about 75 m north of Baltimore Canyon and north of South Toms Canyon. On the basis of studies by Hall and Ensminger (1979), 27 lease tracts on the upper slope were

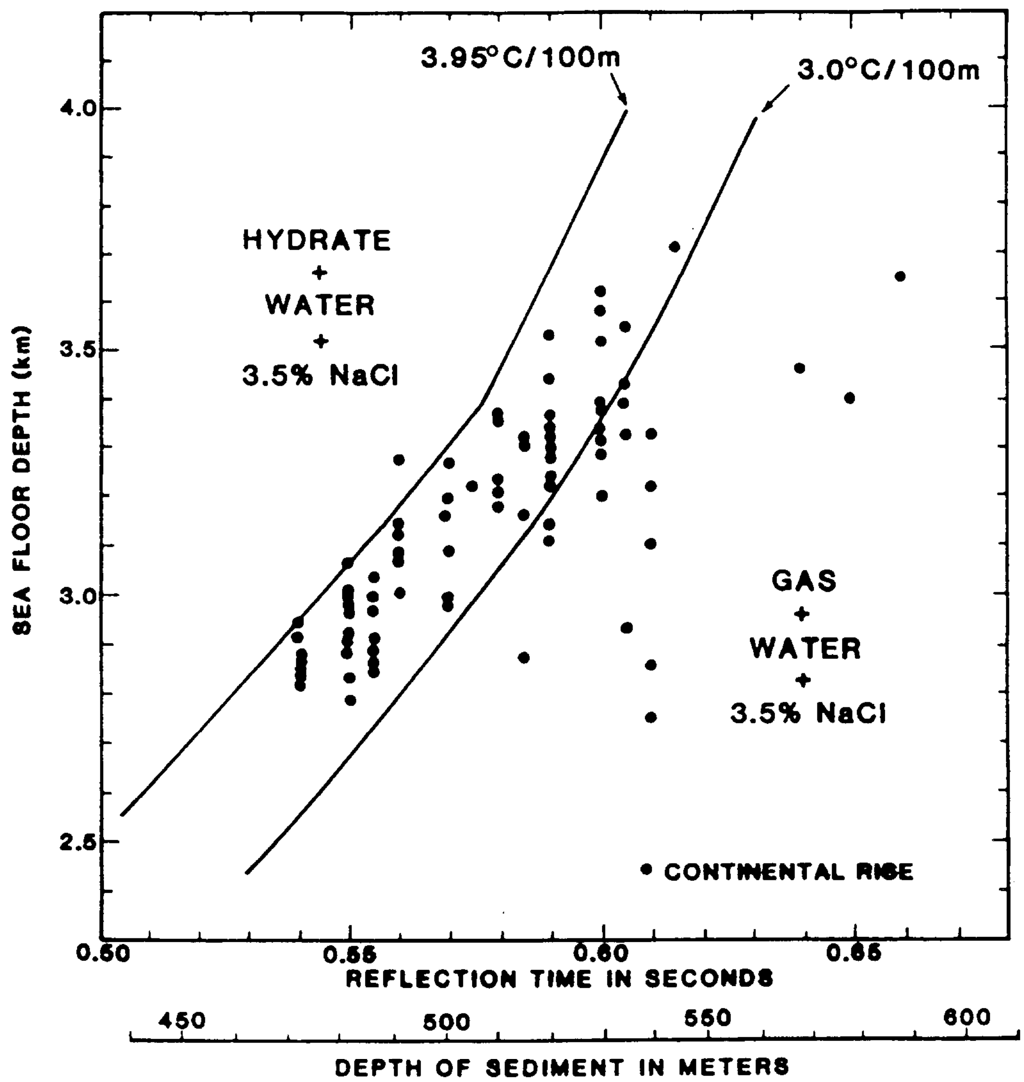



**Figure 19. DEPTH TO BOTTOM SIMULATING REFLECTOR**
**After Tucholke et al. (1977)**

The experimentally derived limits of methane hydrate stability in the presence of sea water are shown for two possible sediment temperature gradients.

withdrawn from Lease Sale 49 because of potential slumping. Considerable erosion can also be documented on the lower continental slope but is largely limited to the erosive activity of turbidity currents.

In contrast to the slope region, the rise has a subdued topography with relatively minor erosion due to current activity. The lower rise may be a region of locally rapid sedimentation as the result of deposition from turbidity currents.

In contrast to the slope region, the rise has a subdued topography with relatively minor erosion due to current activity. The lower rise may be a region of local rapid sedimentation as the result of deposition from turbidity currents.

The effects of sediment erosion on hydrate stability have been discussed by Krason and Ridley (1985) who pointed out that the initial effect is for a local increase in heat flow as the sediment column readjusts to the new thermal regime. As long as the sediment column is under hydrostatic conditions, erosion will have no effect on the pressure regime. However, if gas hydrate growth is sufficient to promote an approach to geostatic pressure conditions, then erosion will cause a slight depressurization of the sediment column. The raising of the base of the hydrate zone due to this unloading is opposed by the cooling of the sediments which lowers the base of the zone. The relative contribution of each factor is uncertain. The ultimate effect is that the base of the hydrate zone will move upward or downward to establish a new equilibrium position either determined by the pressure and temperature (P - T) conditions for gas hydrate stability or the availability of hydrocarbon gas. Assuming that the hydrate zone requires one million years to stabilize after a shift, then Pleistocene and Holocene erosion would have produced gas hydrate zones in varying stages of reequilibration.

It is also interesting to note that DSDP drilling on the continental slope (Sites 107 and 108) and rise (Sites 105 and 106) encountered adverse drilling conditions within the depth section of potential gas hydrate stability. At Sites 107 and 108, strongly consolidated Eocene sediments were drilled within tens of meters of the surface. Consequently, it appears that the common assumption of hydrostatic pressure conditions may be in error for parts of the slope and rise environment, and that a condition intermediate between hydrostatic and geostatic may prevail. This effect may account for some of the scatter observed in Figure 19.

The conclusion is reached that sediment instability on the continental slope and rise will have an effect on the stability of gas hydrates. This effect is to cause a readjustment of the lower gas hydrates. This effect is to cause a shift of the lower gas hydrate boundary to greater depths, as discussed by Krason and Ridley (1985). However, erosion of 50 - 100 m appears to be the maximum observed, suggesting a lowering of the hydrate boundary by about this amount. Such erosional effects are mostly observed on the continental slope, and Paull and Dillon (1981) have suggested that Class 3 reflectors are usually observed to be associated with areas of erosion. Thus, the slope area may be more prone to display Class 3 reflectors than the rise, and could account for the difficulty of recognizing the BSR in slope sediments.

## Gas Hydrate Host Rocks

In assessing the formation and stabilization of gas hydrates, Krason and Ridley (1985) noted that hydrate crystallization would be enhanced in clayey, fine-grained sediments because of the presence of "structured" water associated with clay surfaces, and that the ratio of "structured" to "bulk" water should increase with depth, i.e. sediment compaction. Thus, the potential exists for an increasing volume of hydrates with depth within the sediment column.

Another important factor, not addressed in our earlier report (Krason and Ridley, 1985), is the effect of lithology on hydrate nucleation. From experimental data, Makogon (1978) clearly states that hydrate nucleation is facilitiated in coarse-grained versus fine-grained sediments. This is due to the lowering of water vapor pressure as a consequence of the presence of both bound water and capillary water. The adsorption forces involved in the formation of bound water are such that the depression of water vapor pressure is inversely related to particle diameter. In the case of capillary water, the depression of water vapor pressure is inversely related to the capillary radius which in turn increases with decreased particle diameter. Because at any given temperature and pressure the saturated water vapor pressure required to promote gas hydrate nucleation is fixed, lowering of the water vapor pressure in fine-grained sediments may be sufficient to inhibit nucleation. Thus, in sediment having a range of pore sizes and pore throats determined by grain size, gas hydrate nucleation is initially promoted in the coarser-grained parts of the sediment column, and growth may then spread into the finer-grained sediment. Once nucleation of hydrates has been initiated, the process of gas hydrate growth is then partly determined by the water vapor pressure above the gas hydrates.

The preceding discussion indicates that the nucleation and growth of hydrates is partly determined by the distribution of grain sizes, and hence lithologies, throughout the sediment column that lies within the P - T field of potential hydrate stability. With this in mind, we make the following observations regarding the Baltimore Canyon Trough region:

1. The lower continental slope and rise have been the site of deposition of mainly hemipelagic muds, clays, and silty clays throughout most of Mesozoic and Cenozoic time. Thus, lithologic conditions are not optimal for gas hydrate nucleation, and growth around a few nucleation centers is to be expected. However, with compaction, gas hydrate growth should be accelerated and there should be an increased volume of hydrates as a function of depth.

2. The lower rise may show Pleistocene to Holocene interbedding of coarse clastics and fine muds as a result of turbidite activity. Under these conditions, gas hydrate nucleation would be optimized in the turbidite units, and then spread to neighboring finer-grained sediments. However, a layered, heterogeneous distribution of hydrates is to be expected, with hydrates concentrated in the coarser units.

3. Near the top of the slope are found almost 300 m of generally fine-grained Pleistocene sediments, except in those areas affected by recent erosion. Below about 100 m water depth the Pleistocene, fine-grained sediments thin to less than 20 m and are underlain by strongly compacted Tertiary deposits. Thus, hydrate development in this region may include a significant amount of well-compacted sediment. Such strong compaction should increase the ratio of structured to bulk water and promote hydrate growth once nucleation has been initiated.

## Sedimentary Organic Matter

The flux of organic matter below the zone of sulfate reduction ultimately determines the hydrocarbon generating capability of sediment, either through shallow microbial methane production or deeper thermal maturation. The concept of the organic matter flux is important because, by comparison to the clastic flux, it provides insight to environmental conditions during and prior to deposition. Such information may be unavailable or misleading from an examination of the total organic carbon (TOC) expressed as a sediment percentage.

Complex interactions of natural processes determine the clastic and organic matter flux relation. The most important are:

1. The oxidation - reduction (redox) conditions within the water column. Strongly anoxic conditions preserve organic matter during transport; aerobic conditions lead to destruction of organic matter in the water column.

2. Marine organic productivity which determines the initial organic matter flux into the water column. In marine environments productivity is highest in regions of upwelling, particularly over the continental slope regions.

3. Redox conditions within the shallowest sediments, which may be determined by the general redox conditions in the water column or by sediment input. High sediment flux can produce reducing conditions near the sediment - water interface even in an oxygenated water column.

4. Hydraulic conditions may determine the physical preservation of organic matter. Generally, the organic matter is fine-grained and ultimately is deposited in fine-grained sediments of the slope. The organic matter is usually dominated by marine types (Figure 20). In addition, dissolved organic or finely suspended material may be adsorbed onto clay surfaces and then incorporated into fine-grained sediments. Generally, the shelf region is not optimal for organic matter preservation, excepting possibly resistant terrestrially derived materials (fusain, pollen, spores, etc.). Other exceptions may be shelf regions of restricted oceanic circulation isolated from normal wave and current actions.

FIGURE 20. Organic Matter Type Related to Water Depth in Modern Sediments, U.S. Atlantic Coast, is located in the pocket at the end of the report.

These various factors indicate that in regions of aerobic or mildly anoxic conditions, the flux of organic matter at the sediment - water interface will be low and relatively constant. Its preservation from further oxidative destruction is determined by the clastic input. Thus, the organic carbon flux and clastic input are positively correlated. Under strongly anoxic conditions, the flux of organic matter at the sediment - water interface is high and principally determined by surface productivity. Clastic flux is not a factor in determining the preservation of organic matter but simply acts as a diluent to the percentage of organic matter in the sediment.

Superficially, we would conclude that in anoxic environments the organic matter flux and clastic flux are noncorrelative. However, the commonly observed relationship, e.g. Cretaceous black shales, is a negative correlation. The major reason for this relationship in open ocean environments is the association of widespread anoxia with large-scale marine transgression and the development of large, shallow epicontinental seas. These periods also tend to have attendant mild global climates and much reduced oceanic circulation potentially leading to anoxia. Following marine transgression, the spreading of epicontinental seas results in a reduced clastic flux to the oceans, while the marine organic matter flux may be quite high. Consequently, an inverse relationship is observed.

The depositional environment determines not only the amount of organic matter preserved but also the type. Transport through different redox regimes selectively destroys certain types of organic matter and determines the H/C ratio of the sediment. Oxidation reverses the processes of photosynthesis, releasing $CO_2$ and $H_2O$ from organic matter, as well as a variety of nutrients. Carbohydrates, proteins, and lipids are most easily decomposed, resulting in a fractionation process which selectively concentrates resistant material. In oxidizing environments, woody tissue, spore walls and pollen grains are concentrated, and finally only charcoal is preserved. These components are common in slowly accumulating pelagic clays, and account for the dominance of terrestrial kerogen types in the continental rise and abyssal plain environments (Figure 20).

In reducing environments, oxidative decomposition is very limited. Usually, organic matter breakdown is accomplished through anaerobic bacterial activity, i.e. sulfate reduction releases oxygen which will oxidize available organic matter. Under these conditions the structure of marine organic material is destroyed, leaving an amorphous (sapropelic) residue. Herbaceous and woody material are usually unaltered by these processes.

## Sources of Hydrocarbons

The mix of organic matter types preserved is an important parameter in determining the hydrocarbon products generated. Most oils are derived from a mixture of organic materials but some oils require very specific organic matter types, e.g. aromatic oils - woody type, naphthinic oils - marine algal type. During the earliest stages of thermal maturation, marine and terrestrial organic matter will produce methane. However, herbaceous, coaly and woody terrestrial types are much more gas prone than are marine algal types. Also, temperatures above the "oil window" will also produce methane, which may be accompanied by higher molecular weight gases and condensate.

With reg : the sources of hydrate gases, both biogenic methane and thermogenic m e have been identified (Kvenvolden and Barnard, 1983; Brooks et al., . At the Blake Outer Ridge site, the methane is entirely microbial. Both genic and thermogenic methane are potentially trapped in shallow sediments in the Baltimore Canyon Trough region, but the lack of compositional and isotopic data on shallow sediment gases prevents a quantitative assessment of possible sources. Beneath the upper slope thermogenic gas was tested in the COST B-3 well at approximately 4,800 m. Near the shelf edge, the Texaco 598-1 and Tenneco 642-1 wells also tested thermogenic methane, oil and condensate.

Although these environments are marginally important from the viewpoint of gas hydrate stability, the source of the hydrocarbons may be eastward of their present location, i.e. within the realm of the middle and lower continental slope. The source of hydrocarbons remains a puzzling problem because at the COST B-2 and COST B-3 the deepest sediments penetrated were only marginally mature with regard to hydrocarbon generation. However, there are 5,000 - 7,000 m of Jurassic sediments beneath these wells which may be thermally mature with regard to hydrocarbon generation. Alternatively, the source for hydrocarbons may lie beneath the slope region, implying lateral migration. If this process was accompanied by some vertical migration (as seems inevitable given the buoyancy forces involved), then there may be an upward flux of thermally generated gas into the shallow zone of gas hydrate formation. This process is explored further in the Basin Development section of this report.

Hydrocarbon gas, mainly methane, may also be produced in fine-grained continental slope and rise sediments as a result of microbial reactions involving methane producing bacteria. Such a process has been well documented at many continental slope and rise localities but has not been evaluated at the Baltimore Canyon Trough region. At the Blake Outer Ridge locality, biogenic methane production is a well established process as the main gaseous contributor to gas hydrate formation. Similar lithologies, i.e. hemipelagic muds and silty clays, beneath the slope and rise region of the Baltimore Canyon Trough, and similar environmental conditions may also result in biogenic methane production. However, in the absence of isotopic and chemical data on slope and rise gases it is not possible to evaluate potential gas sources, except in a speculative manner.

### Organic Carbon Flux

The calculated flux values for total organic carbon (TOC) and clastic material for the COST B-2 (shelf edge), COST B-3 (upper slope) and DSDP Sites 105, 106 (lower rise) are shown in Tables 5, 6, and 7 and Figures 21A and B, 22A and B, 23A and B, and 24A and B. The data have been formulated to be compatible with calculations performed for the Blake Outer Ridge. The amount of data available for these flux determinations is variable. The most comprehensive data set is available for the COST wells, whereas the DSDP data set is most complete for Sites 105 and 106 and sparse for Sites 107 and 108.

TABLE 5

## CLASTIC AND TOTAL ORGANIC CARBON (TOC) FLUX, COST B-2 WELL

| Sample depth interval m | Age span m.y.b.p. | Present * porosity % | Clastic sedimentation rate m/m.y. | TOC % | Clastic flux $mg/cm^2/yr$ | TOC flux $mg/cm^2/yr$ |
|---|---|---|---|---|---|---|
| 341 - 350]** | 5 - 12 | 55 | 8 | 0.1 | 2.19 | 0.002 |
| 396 - 405]** | 5 - 12 | 54 | 8 | 0.2 | 2.1 | 0.004 |
| 451 - 460]** | 5 - 12 | 52 | 8 | 0.1 | 2.1 | 0.002 |
| 506 - 515]** | 12 - 14 | 51 | 157 | <0.1 | 41.6 | 0.04 |
| 625 - 634]** | 12 - 14 | 48 | 157 | 0.3 | 41.6 | 0.12 |
| 710 - 716]** | 12 - 14 | 46 | 157 | <0.1 | 41.6 | 0.04 |
| 710 - 716]** | 12 - 14 | 46 | 157 | 0.5 | 41.6 | 0.2 |
| 926 - 936]** | 12 - 14 | 41 | 157 | 1.4 | 41.6 | 0.6 |
| 1090 - 1100 | 14 - 22 | 38 | 5 | 2.4 | 1.3 | 0.03 |
| 1173 - 1182 | 22 - 38 | 36 | 4 | 2.8 | 1.1 | 0.03 |
| 1252 - 1261]** | 38 - 53 | 35 | 13 | 0.9 | 3.4 | 0.03 |
| 1429 - 1423]** | 38 - 53 | 32 | 13 | 1.0 | 3.4 | 0.04 |
| 1520 - 1523]** | 38 - 53 | 30 | 13 | 0.9 | 3.4 | 0.03 |
| 1584 - 1615 | 63 - 71 | 29 | 7 | 0.3 | 1.9 | 0.005 |
| 1648 - 1651 | 71 - 80 | 28 | 17 | 0.5 | 4.5 | 0.02 |
| 2048 - 2051 | 80 - 86 | 23 | 57 | 0.2 | 15.1 | 0.03 |
| 2505 - 2511 | 91 - 106 | 18 | 20 | 2.1 | 5.3 | 0.11 |
| 2696 - 2700 | 106 - 117 | 17 | 27 | 0.5 | 7.1 | 0.03 |
| 2962 - 2965 | 106 - 117 | 14 | 27 | 0.6 | 7.1 | 0.04 |
| 3313 - 3325 | 117 - 112 | 12 | 54 | 2.2 | 14.2 | 0.31 |
| 3431 - 3441 | 122 - 131 | 11 | 30 | 2.6 | 7.9 | 0.21 |
| 3706 - 3715]** | 131 - 136 | 10 | 216 | 6.0 | 56.8 | 3.41 |
| 3886 - 3889]** | 131 - 136 | 9 | 216 | 2.0 | 56.8 | 1.13 |

* Based on exponential depth curve (Sclater and Christie, 1980)
Assumed grain density = 2.65 $g/cm^3$
** Averaged in Figures 19A, B

TABLE 5 (cont)

## CLASTIC AND TOTAL ORGANIC CARBON (TOC) FLUX, COST B-2 WELL

| Sample depth interval m | Age span m.y.b.p. | Present * porosity % | Clastic sedimentation rate m/m.y. | TOC % | Clastic flux $mg/cm^2/yr$ | TOC flux $mg/cm^2/yr$ |
|---|---|---|---|---|---|---|
| 3968 - 3971]** | 131 - 136 | 9 | 216 | 11.5 | 5.68 | 6.53 |
| 3968 - 3971]** | 131 - 136 | 8 | 216 | 6.0 | 5.68 | 3.4 |
| 4078 - 4090]** | 131 - 136 | 8 | 216 | 2.0 | 5.68 | 1.1 |
| 4242 - 4245]** | 131 - 136 | 8 | 216 | 1.1 | 5.68 | 0.6 |
| 4425 - 4428* | 131 - 136 | 7 | 216 | <0.1 | 5.68 | 0.05 |
| 4516 - 4519]** | 131 - 136 | 7 | 216 | 0.6 | 5.68 | 0.3 |
| 4608 - 4611]** | 131 - 136 | 6 | 216 | <0.1 | 5.68 | 0.05 |
| 4699 - 4702]** | 131 - 136 | 6 | 216 | <0.1 | 5.68 | 0.05 |
| 4791 - 4794]** | 131 - 136 | 6 | 216 | <0.1 | 5.68 | 0.05 |
| 4825 - 4830]** | 131 - 136 | 5 | 216 | <0.3 | 5.68 | 0.2 |
| 4846 - 4885]** | 131 - 136 | 5 | 216 | 0.2 | 5.68 | 0.1 |
| 4882 - 4885]** | 131 - 136 | 5 | 216 | <0.1 | 5.68 | 0.05 |

* Based on exponential depth curve (Sclater and Christie, 1980)
Assumed grain density = 2.65 $g/cm^3$
** Averaged in Figures 19A, B

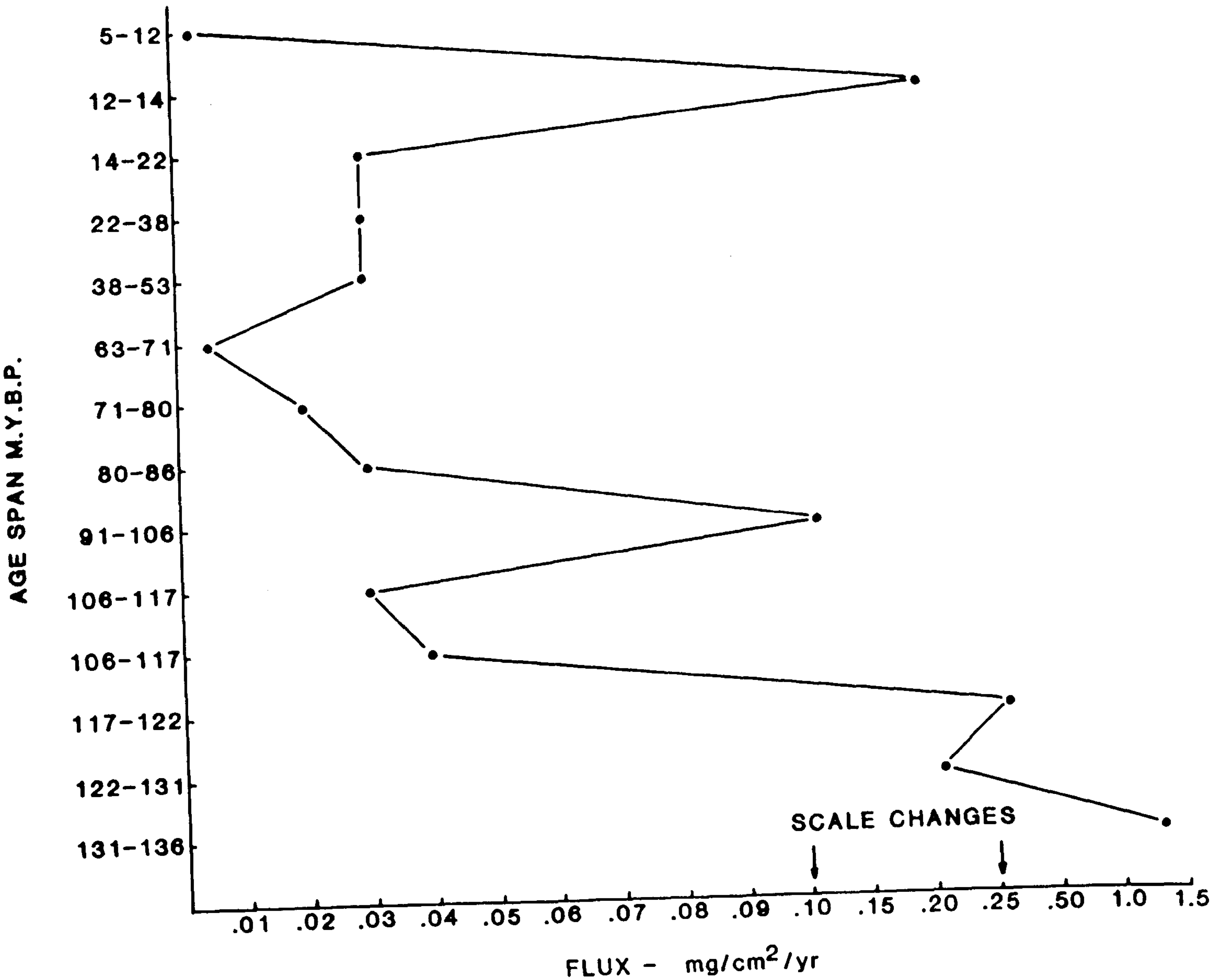



Figure 21A. ORGANIC FLUX, COST B-2 WELL, CONTINENTAL SHELF EDGE, BALTIMORE CANYON TROUGH

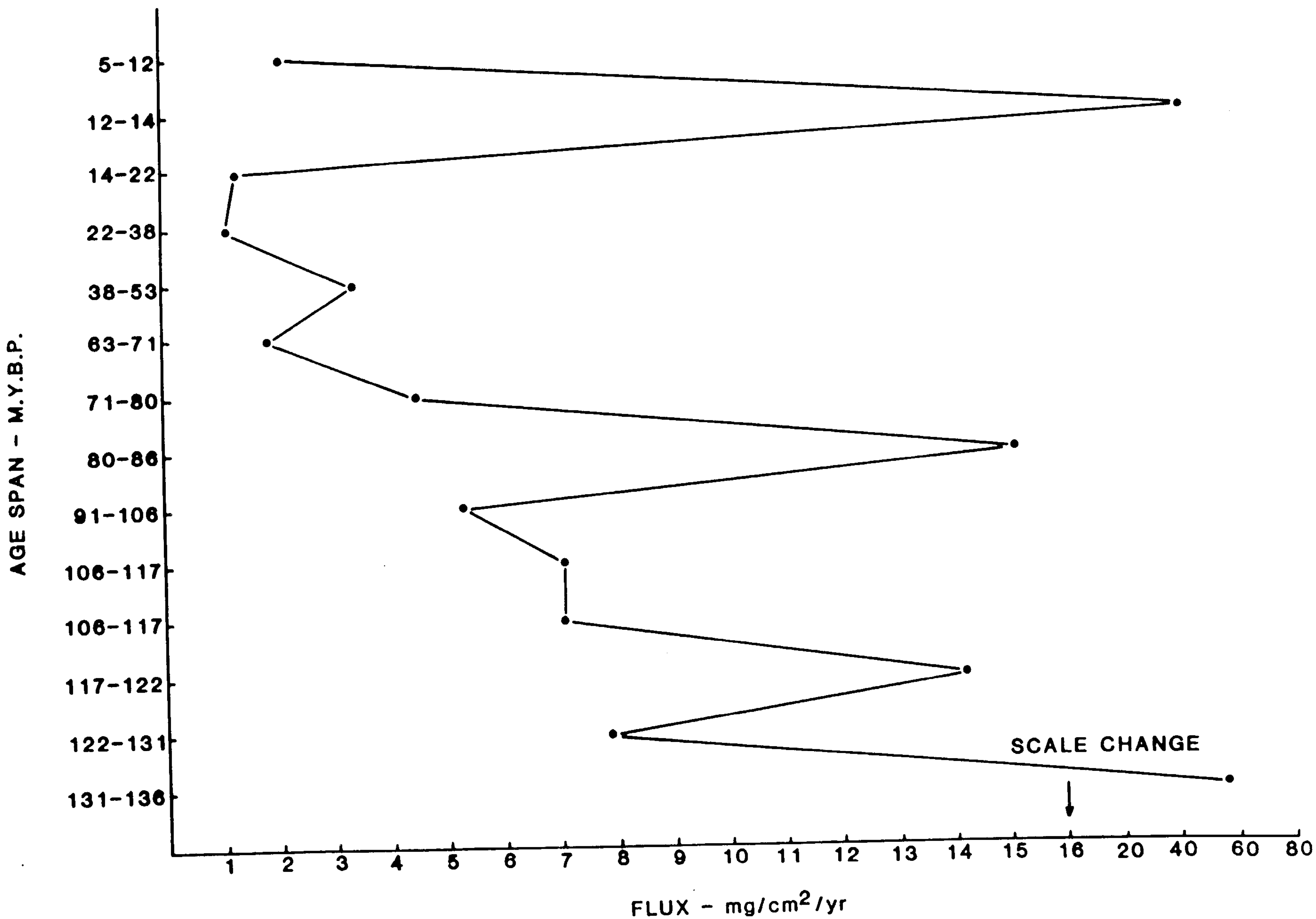



**Figure 21B.** CLASTIC FLUX, COST B-2 WELL, CONTINENTAL SHELF EDGE, BALTIMORE CANYON TROUGH

TABLE 6

CLASTIC AND TOTAL ORGANIC CARBON (TOC) FLUX, COST B-3 WELL

| Sample depth interval m | Age span m.y.b.p. | Present * porosity % | Clastic sedimentation rate m/m.y. | TOC % | Clastic flux mg/cm²/yr | TOC flux mg/cm²/yr | Lithology |
|---|---|---|---|---|---|---|---|
| 1161 | 5 - 12 | 53 | 10 | 1.11 | 2.6 | 0.038 | Clay |
| 1225 | 12 - 14 | 51 | 50 | 1.74 | 13.3 | 0.23 | Clay |
| 1381 | 14 - 22 | 47 | 4 | 3.18 | 1.1 | 0.03 | Clay |
| 1582 | 22 - 48 | 43 | 7 | 1.18 | 1.9 | 0.02 | Shale |
| 1710 | 48 - 53 | 40 | 21 | 0.49 | 5.6 | 0.03 | Shale |
| 1859 | 65 - 70 | 37 | 3 | 0.37 | 0.8 | 0.00 | Shale |
| 2040 | 78 - 82 | 34 | 31 | 1.11 | 8.2 | 0.09 | Shale |
| 2195 | 82 - 86 | 31 | 45 | 1.58 | 11.9 | 0.19 | Silty shale |
| 2350 | 82 - 86 | 29 | 45 | 0.88 | 11.9 | 0.11 | Silty claystone |
| 2505 | 86 - 92 | 27 | 13 | 0.41 | 3.4 | 0.01 | Claystone |
| 2652 | 92 - 100 | 27 | 25 | 1.09 | 6.6 | 0.07 | Silty mudstone |
| 2804 | 100 - 110 | 26 | 8 | 0.77 | 2.1 | 0.02 | Mudstone |
| 2957 | 110 - 117 | 20 | 19 | 0.58 | 5.0 | 0.03 | Limestone? |
| 3139 | 117 - 122 | 15 | 22 | 0.60 | 5.8 | 0.04 | Silty shale |
| 3239 | 122 - 131 | 12 | 42 | 0.72 | 11.1 | 0.08 | Shale |
| 3444 | 122 - 131 | 11 | 42 | 0.62 | 11.1 | 0.07 | Silty shale |
| 3597 | 122 - 131 | 10 | 42 | 1.05 | 11.1 | 0.12 | Shale |
| 3749 | 136 - 142 | 8 | 53 | 0.68 | 14.1 | 0.10 | Shale |
| 3901 | 136 - 142 | 8 | 53 | 0.84 | 14.0 | 0.12 | Shale |
| 4054 | 136 - 142 | 7 | 53 | 0.80 | 14.1 | 0.11 | Shale |
| 4176 | 142 - 150 | 11 | 68 | 0.39 | 18.0 | 0.07 | Shale |
| 4359 | 142 - 150 | 10 | 68 | 1.10 | 18.0 | 0.20 | Shale |
| 4542 | 142 - 150 | 9 | 68 | 1.13 | 18.0 | 0.20 | Shale |
| 4755 | 150 - 158 | 8 | 15 | 2.18 | 4.0 | 0.09 | Shale |

* Based on exponential depth curve (Sclater and Christie, 1980)
Assumed grain density = 2.65 $g/cm^3$
** Averaged in Figures 19A, B

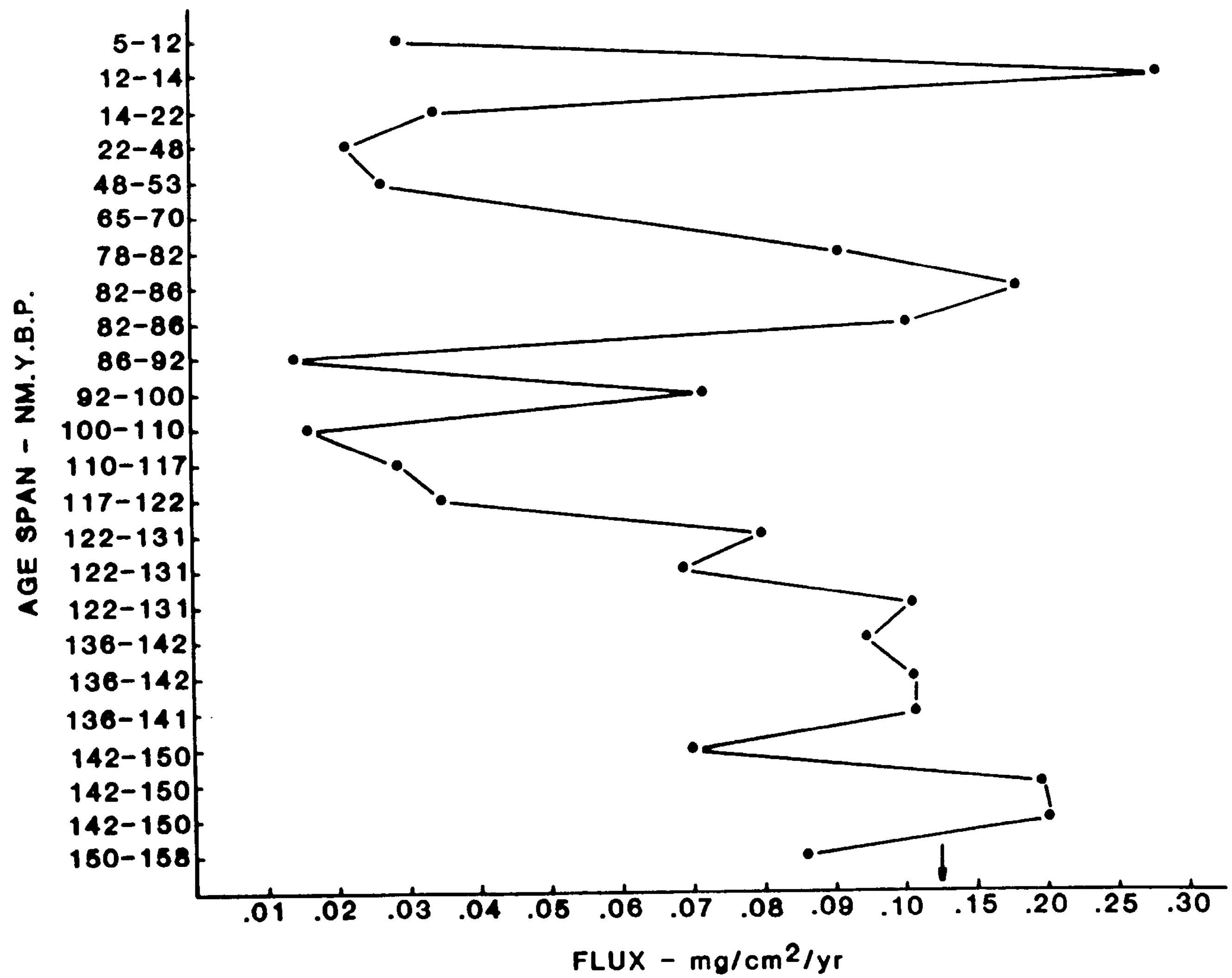



Figure 22A. ORGANIC FLUX, COST B-3 WELL, UPPER CONTINENTAL SLOPE, BALTIMORE CANYON TROUGH

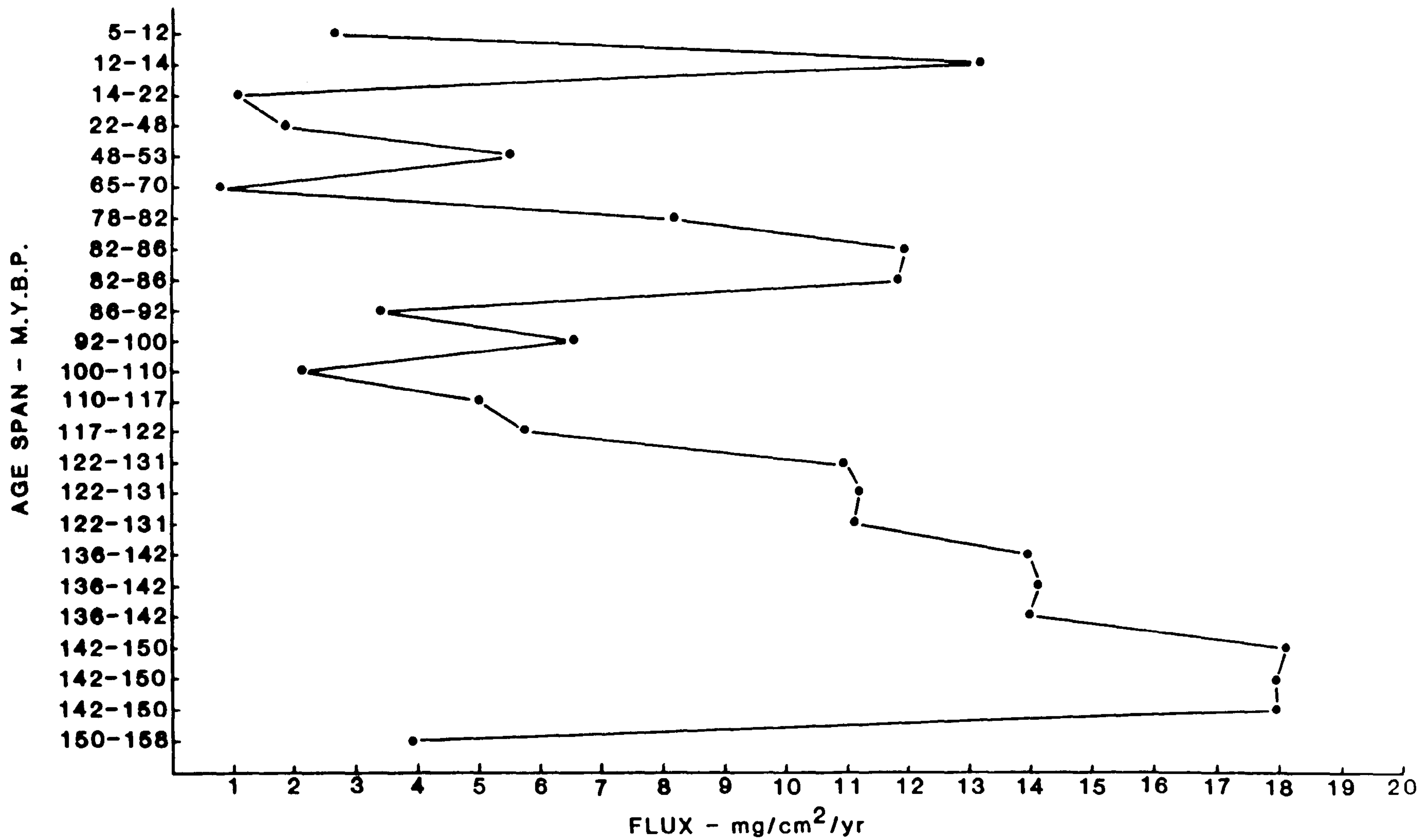



**Figure 22B.** **CLASTIC FLUX, COST B-3 WELL, UPPER CONTINENTAL SLOPE, BALTIMORE CANYON TROUGH**

TABLE 7

## CLASTIC AND TOTAL ORGANIC CARBON (TOC) FLUX
## DEEP SEA DRILLING PROGRAM (DSDP) SITES 105, 106

| Sample depth interval m | Age span m.y.b.p. | Present * porosity % | Clastic sedimentation rate m/m.y. | TOC % | Clastic flux $mg/cm^2/yr$ | Organic flux $mg/cm^2/yr$ | Lithology |
|---|---|---|---|---|---|---|---|
| Site 108: | | | | | | | |
| 43 - 75 | 43 - 45 | 20 | 11.2 | 0.17 | 29.0 | .0049 | Light gray chalk |
| Site 106: | | | | | | | |
| 0 - 343 | 0 - 2.2 | 48 | 85.0 | 0.43 | 22.5 | .09 | Sand, silt, clay |
| 366 - 456 | 22 - 47 | 42 | 32.5 | 0.47 | 8.6 | .04 | Hard, green silty clay |
| 553 - 560 | 4.7 - 11.5 | 40 | 14.1 | 0.43 | 3.7 | .02 | Hard, silty clay |
| 755 - 942 | 11.5 - 20 | 32 | 21.6 | 0.61 | 5.7 | .03 | Hard, silty clay & sandstone |
| Site 105:** | | | | | | | |
| 31 - 34 | 0 - 28 | 50 | 7.1 | 0.61 | 1.9 | .002 | Greenish gray hemipelagic clay |
| 289 - 310 | 92 - 100 | 45 | 1.7 | 0.10 | 0.45 | .01 | Black to gray clay |
| 313 - 373 | 100 - 110 | 43 | 3.7 | 0.98 | 0.98 | .009 | Black to gray clay |
| 385 - 386 | 110 - 116 | 42 | 1.5 | 2.95 | 0.39 | .01 | Gray clay |
| 403 - 458 | 116 - 137 | 40 | 2.0 | 1.46 | 0.53 | .008 | Limestone |
| 466 - 551 | 137 - 142 | 38 | 12.0 | 0.48 | 3.2 | .01 | Limestone |
| 558 - 613 | 142 - 145 | 36 | 15.5 | 0.11 | 4.1 | .004 | Limestone |

* Based on exponential depth curve (Sclater and Christie, 1980)
Assumed grain density = 2.65 $g/cm^3$

** This site contains 186 m of Tertiary silty clay between 100 m and 286 m subbottom, of undetermined age. The average TOC is 0.2%.

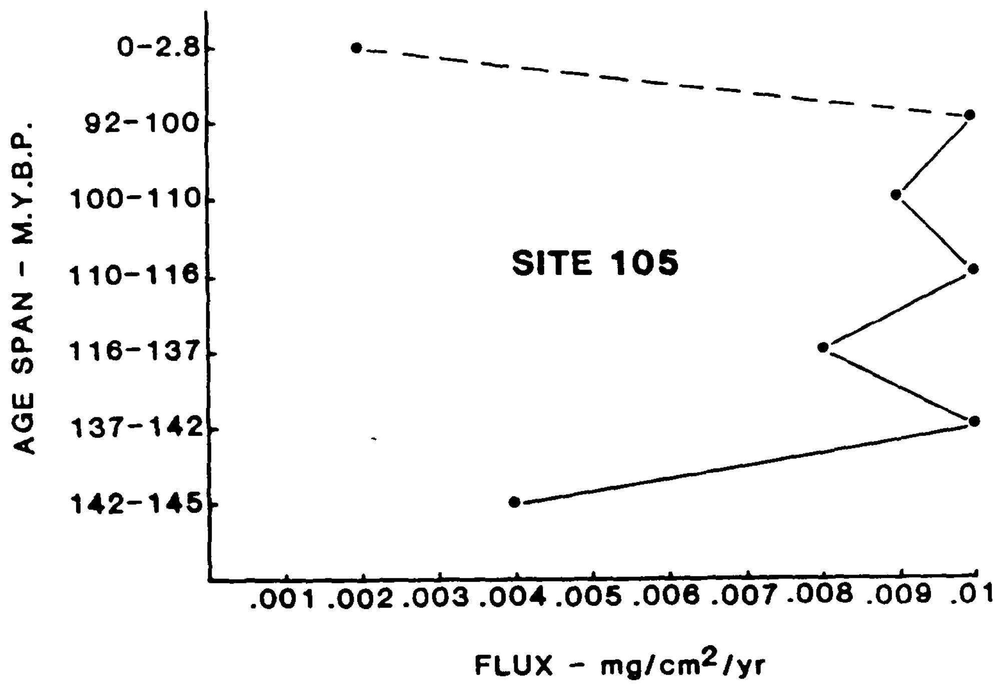



**Figure 23A. ORGANIC FLUX, DSDP LEG 11, SITE 105, LOWER CONTINENTAL RISE, BALTIMORE CANYON TROUGH**

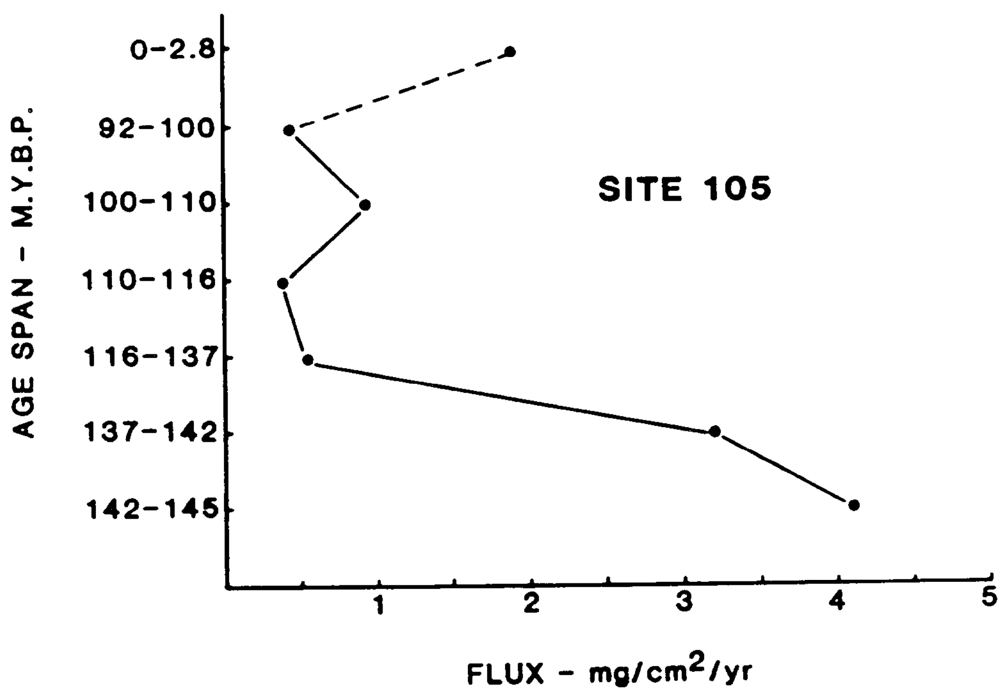



Figure 23B. CLASTIC FLUX, DSDP LEG 11, SITE 105, LOWER CONTINENTAL RISE, BALTIMORE CANYON TROUGH

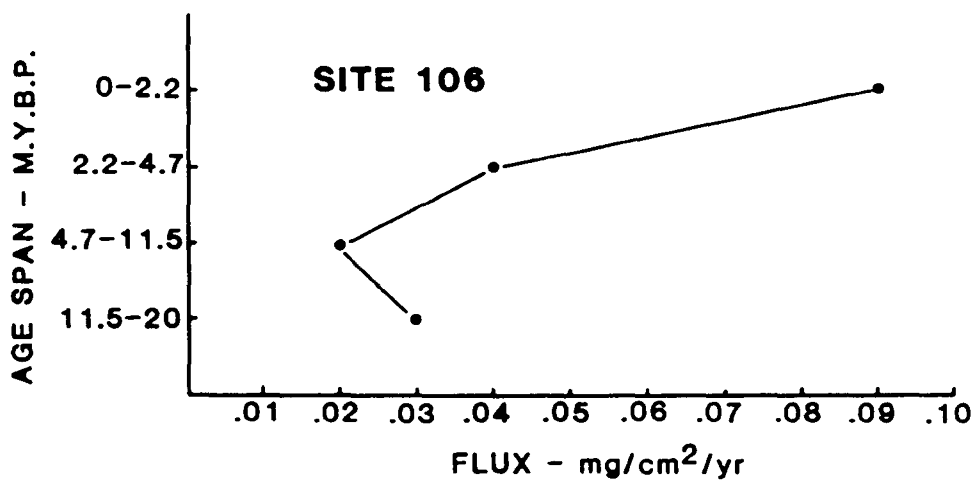



**Figure 24A. ORGANIC FLUX, DSDP LEG 11, SITE 106, LOWER CONTINENTAL RISE, BALTIMORE CANYON TROUGH**

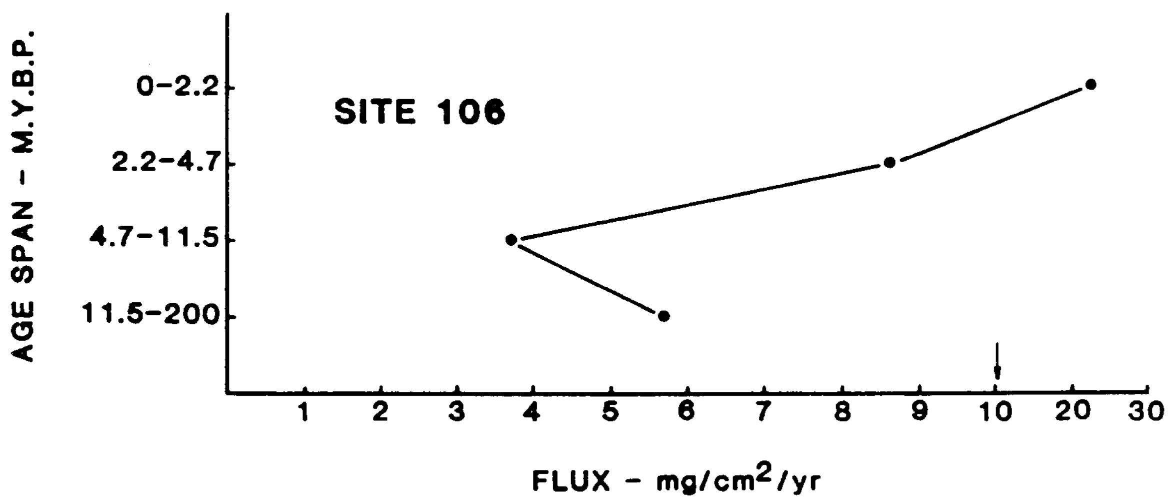



**Figure 24B. CLASTIC FLUX, DSDP LEG 11, SITE 106, LOWER CONTINENTAL RISE, BALTIMORE CANYON TROUGH**

These data indicate the following:

1. The organic flux on the lower rise (and presumably the deeper abyssal plain) is very low, and is unlikely to support biogenic methane production. This conclusion applies throughout the Mesozoic and Cenozoic sections.

2. The "background" fine-grained clastic fluxes in the outer shelf, upper slope, lower rise environments (and presumably over other parts of the rise and slope) are comparable throughout the time span under consideration.

3. At both the COST B-2 (outer shelf) and COST B-3 (upper slope) wells the background organic and fine-grained clastic fluxes are interrupted by flux "spikes" which represent periods of extraordinary clastic input and organic matter preservation.

4. Late Jurassic and Early Cretaceous time witnessed an extraordinary organic matter flux over the outer continental shelf and upper continental slope environments but not in the continental rise area. This suggests that fine-grained Upper Jurassic and Lower Cretaceous lithologies have potential as sources of thermogenic oil and gas.

5. The general positive correlation between organic and clastic fluxes suggests that the slope and outer shelf regions have not experienced strongly reducing conditions throughout the history of the margin. However, the negative flux correlation observed for the Cretaceous black shales at the COST B-2 well indicates that the widespread Cretaceous anoxic event(s) may be locally reflected on the upper part of the margin.

6. A middle Miocene organic flux high is observed in both COST B-2 and COST B-3 mudstones, which may be of regional extent, although not evident in the continental rise. Such lithologies are observed at shallow depth within the present zone of potential gas hydrate stability, and would therefore make a large contribution to biogenic methane production. The remaining Tertiary section indicates a low organic flux, probably insufficient to make a significant contribution of biogenic methane to hydrate production.

### Vertical Distribution of Gas Hydrates

Above the lower stability boundary for gas hydrate formation the distribution of hydrates will be heterogeneous because of:

1. The heterogeneous distribution of permeability.

2. The heterogeneous distribution of organic matter, and therefore biogenic methane, if the latter is a major contributor of hydrate gas.

3. The heterogeneous distribution of pore sizes.

4. Potential limitations on pore water supersaturation determined by marginally productive concentrations of organic matter.

5. Trapping of ascending thermogenic gas or released biogenic gas in the lower hydrate zone resulting in gas starvation of the upper zone.

For the Blake Outer Ridge site biogenic methane contributed to about 5% hydrate production, i.e. 5% of pore volume filled with hydrates. At the Baltimore Canyon Trough site, the flux of organic matter is also marginally capable of sustaining pore water saturation with respect to methane and a similar percentage value is appropriate.

However, gas hydrate destruction and the release of large volumes of methane and fresh water at the lower stability boundary increases gas hydrate formation and focuses our attention on this lower zone as a potentially large reservoir of gas locked in gas hydrates and also a seal to underlying gas.

The effect of the release of fresh water during gas hydrate destruction is shown schematically in Figure 25. Fresh water may ascend into the lower gas hydrate zone, assuming sufficient permeability, as a result of vertical displacement during compaction. Brine within the lower zone may diffuse downwards into the fresh-water zone beneath, and fresh water will also tend to rise due to buoyancy. Within the lower gas hydrate zone the introduction of low salinity pore fluids causes the phase equilibrium to be disturbed from a divariant system of hydrates + methane + brine to a trivariant system of hydrates + brine (Figure 25). Thus, gas hydrates will form at the expense of methane + brine increasing the volume of hydrates in the lower zone, if permeability is sufficient to allow access of methane from below into the lower zone.

It is important also to assess if the lower gas hydrate zone will grow as a function of time or reaches a "steady state", i.e. the rate of upward growth is balanced by the rate of downward destruction. In a water-dominated pore system, the growth of a concentrated zone of hydrates is determined by the continuous supersaturation of a small volume of the fluid with methane. This "interfacial" supersaturation occurs by volume diffusion of methane through the hydrates to the hydrate-water interface, promoting further gas hydrate growth. Although at any specific time, the bulk volume of pore water will be saturated with methane (Makogon, 1978), the conversion of all pore fluid to hydrates requires that all the fluid be incrementally supersaturated with methane. This statement is self-evident, because the concentration of methane in saturated pore fluid is less than 3% of the methane concentration in hydrates. Thus, if only enough methane is available to saturate the pore fluid, this is an insufficient condition for hydrate formation. Here we assume that the methane requirement for hydrate development is thirty times that required to saturate the pore fluid, based on the methane concentration in fully hydrated methane hydrate.

Since biogenic methane production beneath the continental slope and rise in this region appears to be inadequate to meet the requirement for continuous gas hydrate formation, the source of gas may be from the dissociation of hydrates at the lower boundary. In order for a concentrated hydrate zone to

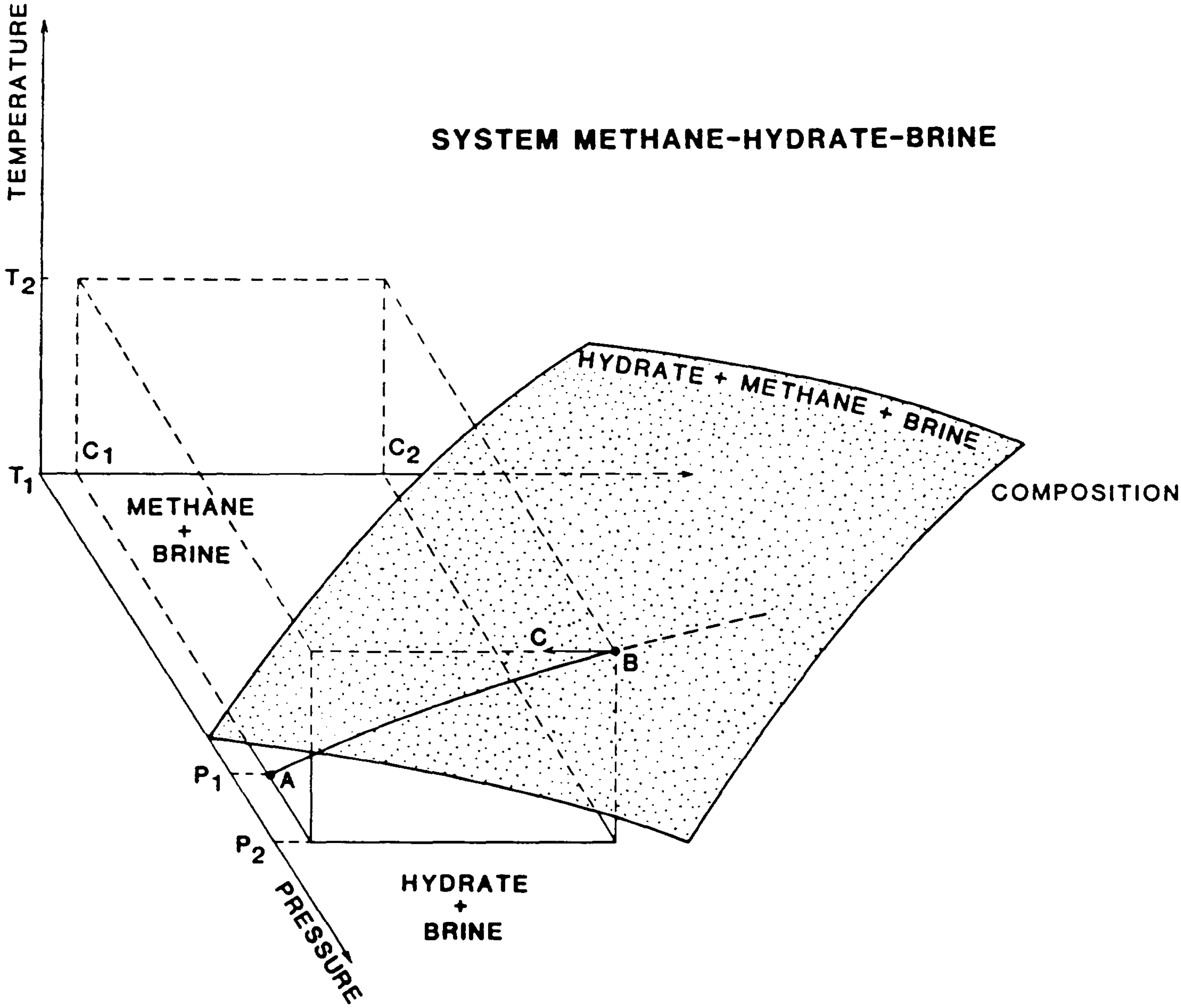



**Figure 25. SCHEMATIC DIAGRAM OF PHASE RELATIONS IN POLYBARIC-POLYTHERMAL HYDRATE SYSTEM**

Showing relations between temperature (T), pressure (P), and fluid composition (C). The hydrate + methane + brine divariant equilibrium is shown as a stippled surface cutting through P-T-C. Projections of this surface onto the P-T plane provide the equilibrium curves shown in Figure 4-10 of the DOE Hydrate Handbook (1983). Point A represents the trivariant hydrate equilibirium at the sediment - water interface (C1 = sea water composition; P1 = hydrostatic pressure; T1 = bottom-water temperature). The line A-B represents the P-T-X evolution during sediment burial. At point B the limit of hydrate stability is reached, i.e. the divariant surface is intersected, at pressure P2. The dissociation of hydrate forces the equilibrium along BC, and isobaric-isothermal line; this in turn promotes further hydrate crystallization.

develop, gas has to migrate back into the zone of hydrate stability. Two mechanisms are available, vertical transport in response to a potential hydrostatic head difference, which requires the lower hydrate zone and the gas zone beneath to be permeable to gas flow, and diffusion in response to a chemical potential gradient. If the hydrate and gas zones are permeable then vertical advection will be the dominant transport process. If the zone is impermeable then the slower process of chemical diffusion dominates.

The physical conditions close to the lower hydrate boundary are critical in determining the development of an underlying gas reservoir and a lower hydrate zone of potential resource quality. The probability that most offshore hydrate zones develop in hemipelagic silty clays and argillaceous sediments severely restricts the potential for an underlying gas reservoir of economic value.

Suppose that during the initial stages of hydrate development the lower hydrate zone pores contain approximately 10% by volume of gas hydrates as a result of bacterial methanogenesis. Subsequent destruction of the gas hydrates releases 12 wt % (50 volume %) of methane and 50 volume % of fresh water at a hydrostatic pressure of 310 atm. (assuming 2,500 m water depth + 600 m sediment depth). The gas exists as a free phase in the pores. If the porosity is 40%, the gas saturation is 5% and the reservoir estimate is 6.2 $m^3$ of gas per $m^3$ sediment at standard temperature and pressure (STP).

In order to accumulate the gas phase further it is necessary for the capillary pressure (Pc) to exceed the displacement pressure (Pd), otherwise the fluid phase will remain inert. The displacement pressure is inversely related to pore size and hence to permeability. For argillaceous sediments the permeability is on the order of $10^{-6}$ - $10^{-7}$ and displacement pressures are correspondingly high, in the range of 150 - 250 atm. In the case of a gas reservoir these excess pressures develop as a result of density differences between the fluid and gas phase, according to:

$$P = (\rho w - \rho g)h$$

where

P = excess capillary pressure
$\rho w$, $\rho g$ = density of water, gas respectively
h = height of gas column

Such high excess pressures can be achieved by gas columns approximately 1,700 m high, suggesting that the gas will remain dispersed through the sediment until such a value is reached. Also, at 5 - 10% gas saturation, the permeability of fine-grained sediments to the gas phase approaches zero and extremely low flow rates of gas are to be expected (Figure 26).

In this situation the timing of development of a gas reservoir through displacement of pore fluid is determined by the rate at which hydrate-bearing sediment passes below the lower stability boundary and adds gassy sediment to the underlying column. Assuming that the hydrate zone adds gas at the constant rate indicated above, then the time necessary to develop a gassy column 1700 m high can be computed for various sediment flux rates (Table 8).

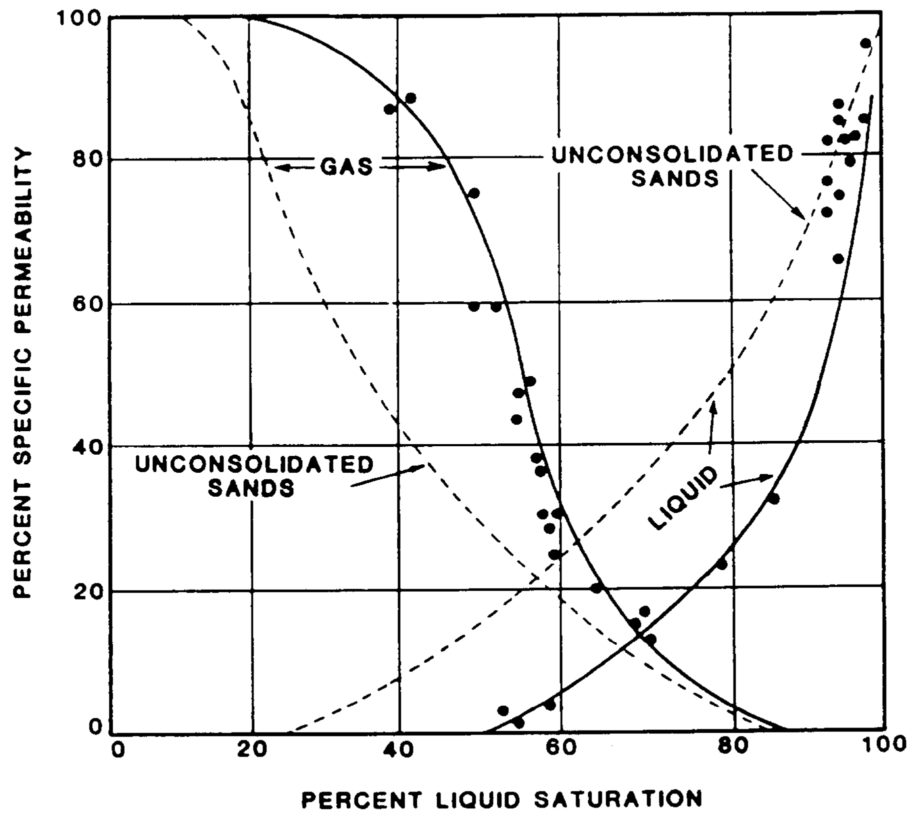



**Figure 26. RELATIONS BETWEEN PORE SYSTEM SATURATION TO GAS AND FLUID PERMEABILITY**

**After Dickey (1981)**

The curves represent unconsolidated sand and permeable sandstones, but similar relations will exist in argillaceous sediments. Note that at liquid saturations above 70% the permeability to gas is less than 10%. At 80% pore fluid saturation, the sediment is essentially impermeable to gas flow.

TABLE 8

## TIME REQUIRED TO DEVELOP 1,700 m SEDIMENT COLUMN AS A FUNCTION OF SEDIMENT FLUX*

| Clastic Input $mg/cm^2/yr$ | Time m.y. |
|---|---|
| 1 | 310 |
| 2 | 155 |
| 5 | 62 |
| 10 | 31 |
| 15 | 22 |
| 20 | 15 |

* Porosity assumed to be 30% below 600 m datum.

These data indicate that at low flux rates, gas reservoirs are unlikely to develop within the time framework for continental margin basin evolution, and that even at high clastic fluxes the time requirements are still substantial if the hydrate zone contains less than 10% hydrates.

Alternatively, the gas reservoir may accumulate rapidly if the lower hydrate zone develops to the stage where a significant part of the sediment volume is composed of hydrates so that upon decomposition a larger volume of gas is liberated. It should be remembered, however, that even in the situation of 100% pore saturation with gas hydrates, the resultant decomposition will produce a pore saturation of about 50% with respect to gas if the excess capillary pressure is insufficient to displace the fluid phase. In this situation the reservoir potential is approximately 62 $m^3$ gas/$m^3$ sediment at STP.

Our discussion so far suggests the following conclusions:

1. The probability that the slope and rise sediments are fine-grained lithologies with very low permeabilities requires extremely high excess gas pressures in order to displace pore fluids and accumulate reservoir volumes of gas.

2. High excess gas pressures can only be achieved through development of a dispersed gas "column" of 1,700 m, i.e. a thickness of 1,700 m of gassy sediment has to accumulate beneath the gas hydrate zone.

3. Permeability to gas flow can be achieved if the dissociation of gas hydrates produces greater than about 15% gas saturation of the pores. This requires the dissociation of approximately 25 - 30% volume percentage of gas hydrates, which implies a lower gas hydrate zone substantially enriched in gas hydrates compared to the overall gas hydrate zone.

4. Production of the underlying gas reservoir would have to take into account low permeability and potentially poor induration of the host rock.

These conclusions are not encouraging with regard to the reservoir potential of underlying gassy sediments if the latter are argillaceous. However, the reservoir potential may be improved under the following circumstances:

1. If the sediments beneath the continental shelf slope break and upper continental slope are more porous and permeable as a result of progradation of coarser clastics.

2. If porous and permeable turbidite sands are interbedded with lower continental slope and rise hemipelagic sediments, thus providing good quality reservoirs. This situation may indeed be found based on the observations of Poag (1985) whereby large-scale slope erosion (and hence turbidity activity) can be recognized in the Baltimore Canyon Trough region at various times through the Tertiary and Quaternary.

The question then arises regarding the movement of methane from the underlying gassy sediments upwards into the hydrate zone. Two methods are possible, diffusion of gas through a pore water medium and permeation through a continuous gas medium. Here, we examine the latter as a mechanism to transfer gas back into the hydrate zone.

We have previously indicated that the slope and rise argillaceous sediments will be almost impermeable to gas flow. Under conditions where the pores are entirely filled with gas the permeability may be as low as $10^{-7}$ md (Nesterov and Ushatinkii, 1971; Pandey et al., 1974). This is an unrealistic situation because the pores within the hydrate zone will be almost completely filled by pore fluid and hydrates. Thus, the permeability to gas may be reduced further by several orders of magnitude (Figure 26) to a value approaching $10^{-10}$ md. Darcy's Law can then be applied to calculate the flow rate of gas through the hydrate zone as a function of gas permeability, which can then be converted to a gas flux (Figure 27).

The growth of a basal gas hydrate zone requires that the rate of formation of gas hydrates exceed the rate of gas hydrate destruction due to the downward movement of sediment out of the gas hydrate stability field. The controlling factors for these conditions are as follows:

1. Rate of upward migration of methane. Controlled by sediment permeability and/or diffusion rate for methane.

2. Sediment porosity.

3. Pore fluid supersaturation concentration, with respect to methane, for hydrate formation.

4. Sedimentation rate.

These factors interact in such a way as to control the growth or destruction of the lower hydrate zone. Figure 28 indicates the rate of growth of the lower zone at a constant permeability for various sediment flux rates. An example is shown below.

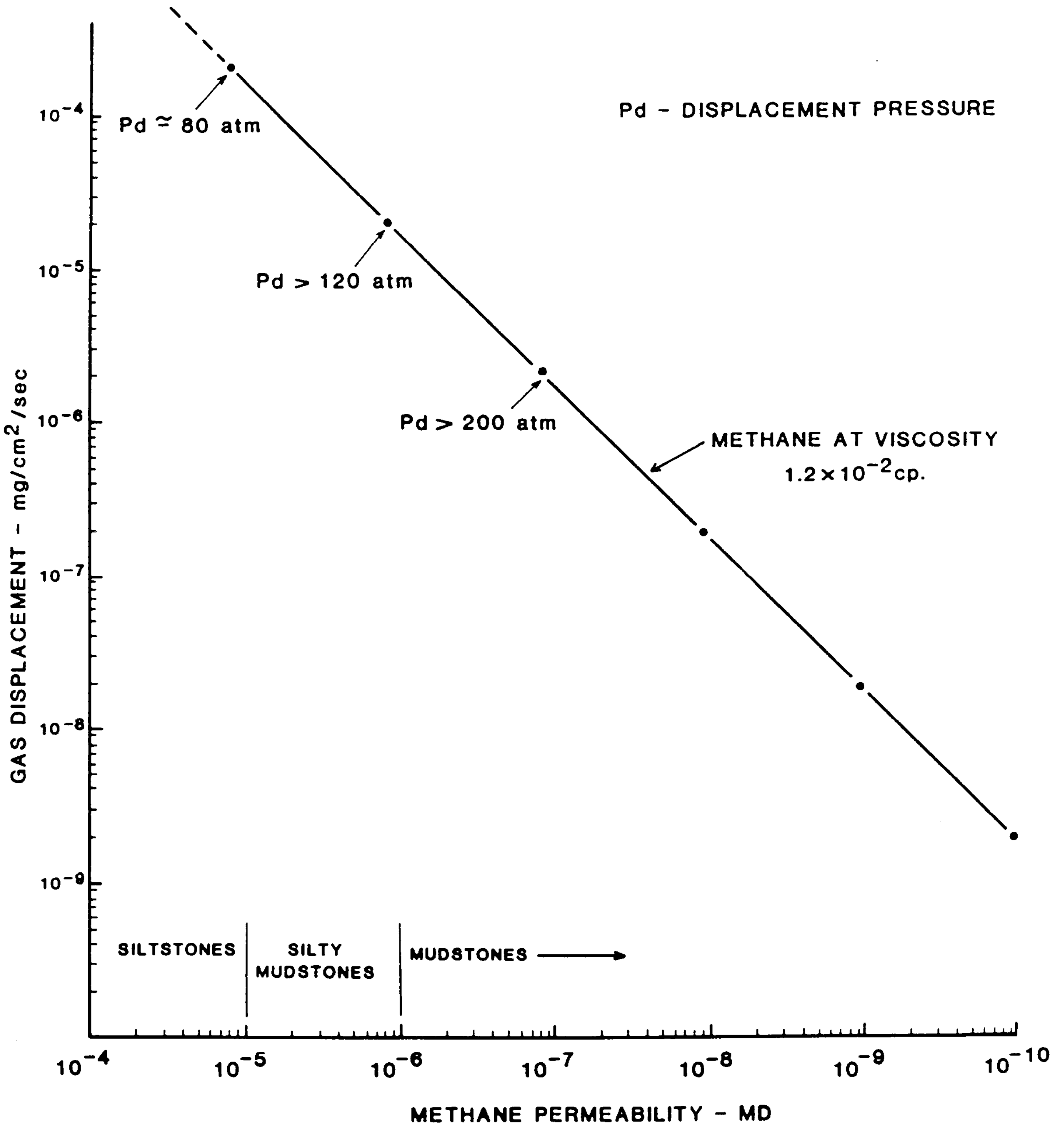



**Figure 27. GAS DISPLACEMENT VERSUS PERMEABILITY FOR METHANE**

Gas displacement calculated based on Darcy's law, from flow rate, assuming methane density of 0.25g/cm$^3$ at 2500m water depth and 600m thick sediment and methane behavior as an ideal gas.

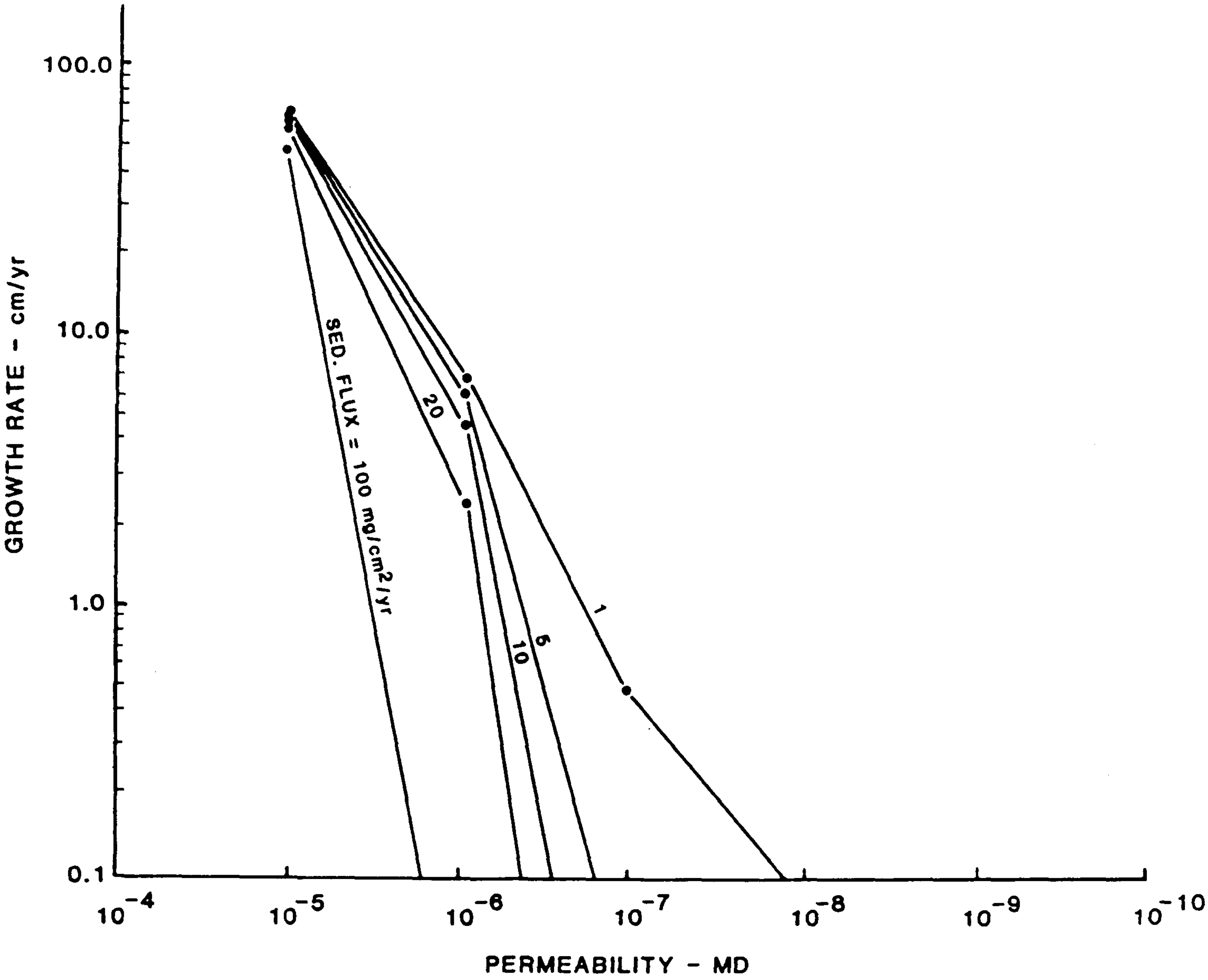



**Figure 28. GRAPH OF HYDRATE ZONE GROWTH RATE VERSUS PERMEABILITY TO GAS FOR DIFFERENT SEDIMENT FLUX VALUES**

The gas hydrate zone growth rate applies to the zone where the pore space is 100% filled with gas hydrate (a disseminated hydrate zone).

Example:

Conditions:
Sedimentation rate = 1 $mg/cm^2/yr$
Sediment density = 2.65 $g/cm^3$
Gas permeability = $10^{-7}$ md
Hydrate methane requirement = 82 mg/g
Porosity = 40%

Calculation:
Water flux = 0.24 $mg/cm^2/yr$
Gas flux = 29.8 $mg/cm^2/yr$

Hydrate destroyed at rate of 0.24 cm/yr
Hydrate formed at rate of 0.73 cm/yr
Net hydrate gain = 0.49 cm/yr

Thus, assuming no reduction in permeability the lower zone would grow at a rate of approximately 1 meter per 200 years. For the above stated conditions, a reduction in permeability below 8 x $10^{-8}$ md would result in no further net hydrate growth.

Note the following:

1. For any sediment flux rate there is a critical permeability below which the rate of hydrate growth is less than the water flux, i.e. the lower zone will not grow upwards.

2. For sediment flux rates of 1 to 10 $mg/cm^2/yr$ the critical permeabilities are in the range of $10^{-6}$ to $10^{-7}$ md.

3. If the growth of gas hydrates severely reduces permeability to gas flow, then the already developed lower hydrate zone will begin to thin as a function of time until permeability increases above some critical value.

4. Assuming that diffusion of methane over large distances is a slower process than permeation, diffusion is unlikely to play an important part in the formation of the lower gas hydrate zone.

5. Growth of nodular and massive hydrate zones requires a special process other than pore system permeability. We suggest that reestablishment of local high permeability zones due to microfracturing is a viable process.

6. In the natural sediment system, the continued growth of gas hydrates must lead to a reduction in permeability and ultimately prevent further hydrate growth. Thus, the thickness of the lower hydrate zone is ultimately determined by the rate of permeability reduction. Also, as the permeability is reduced the hydrates grow at a continuously decreasing rate.

7. The development of a lower zone of enriched, disseminated gas hydrates results in a change in the sediment physical properties. This may enhance the development of microfractures and, hence, local high permeability zones.

8. We would speculate that the thicknesses of lower hydrate zones should be considered on the meters or tens of meters scale, but not larger scale.

## Gas Hydrate Potential of Lower Continental Rise

The seismic data of Tucholke et al. (1977) indicate that BSRs are restricted to the upper continental rise between 2,200 - 3,500 m water depth. We have previously suggested that the area of gas hydrates may extend further into shallow water on the continental slope based upon relations at the Blake Outer Ridge.

Here, we note that the possibility also exists for gas hydrate development at the Hatteras Outer Ridge (Figure 29) based upon its evolutionary similarity to the Blake Outer Ridge. In particular we note the following:

1. The Hatteras Outer Ridge developed above the $A^u$ unconformity by rapid sedimentation from abyssal boundary currents.

2. The Hatteras Outer Ridge is about 500 m high and composed of fine-grained sediments lying in about 4,500 m of water.

3. The sedimentation rate is probably high for the abyssal environment and may have resulted in the formation of anoxic conditions.

4. The sediments are preexisting slope sediments redistributed and redeposited by the interaction of the Western Boundary Undercurrent and the Gulf Stream. The sediments may therefore be associated with a reasonable organic matter flux.

5. The western boundary of the Hatteras Outer Ridge has been flooded with turbidites containing sandy and silty beds which may provide reasonable reservoir lithologies for gas hydrates, as well as finer-grained lithologies which may be methane source beds (Figure 30).

6. The hydrodynamic model developed by Tucholke and Laine (1982) to explain the development of the Hatteras Outer Ridge is very similar to that of Bryan (1970) to explain the development of the Blake Outer Ridge (Figure 31).

7. The development of the Hatteras Outer ridge involves extensive current activity and fan-type deposition but the sediment sources were upstream of the Western Boundary Undercurrent and from more local slope environments.

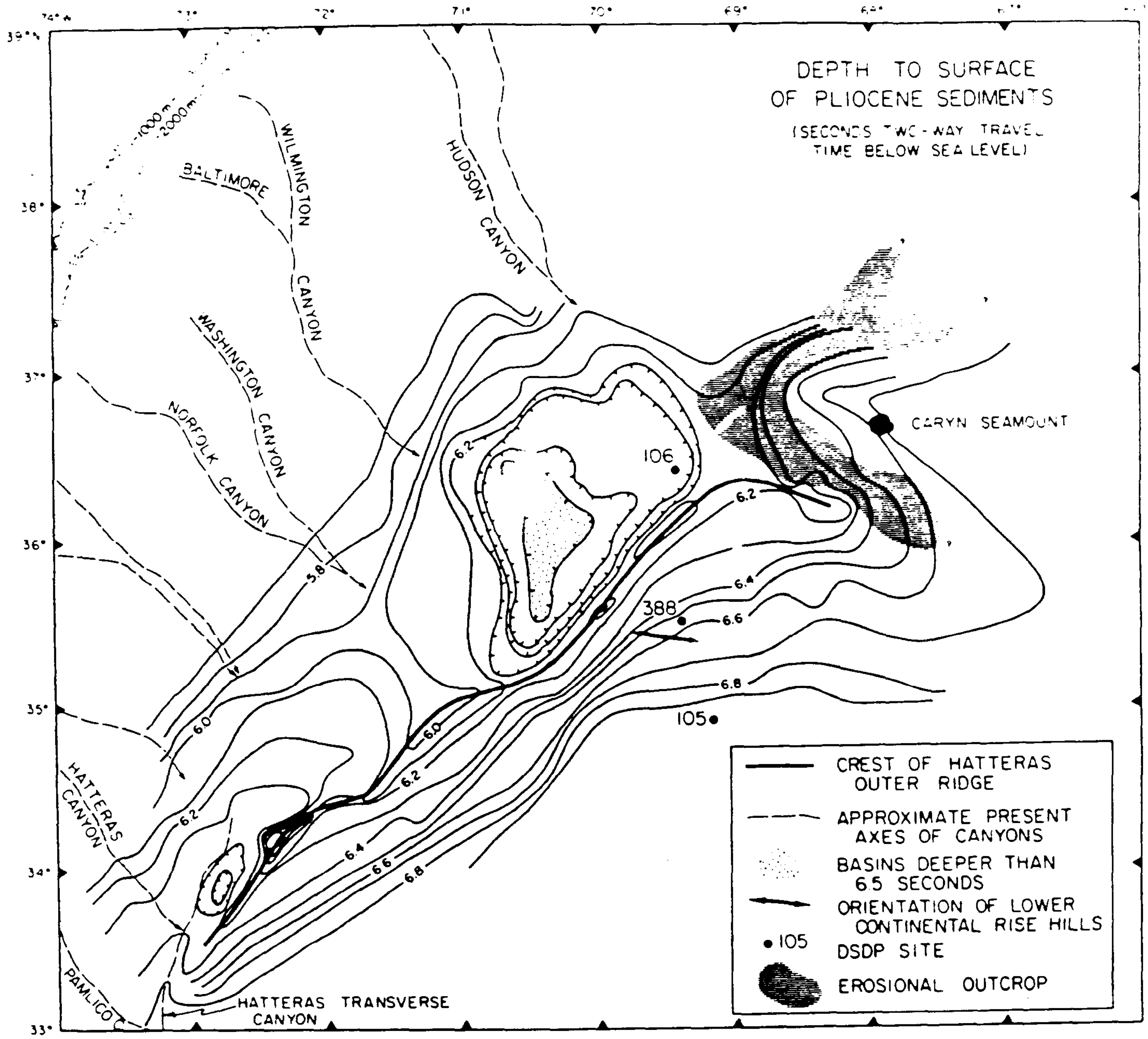



**Figure 29. GEOMORPHOLOGY OF THE HATTERAS OUTER RIDGE BASED UPON (LAMONT-DOHERTY GEOLOGICAL OBSERVATORY) SEISMIC SECTIONS**

**After Tucholke and Laine (1982)**

**The morphology was constructed after removing overlying or onlapping turbidites. Note that the Ridge largely parallels the rise contours.**

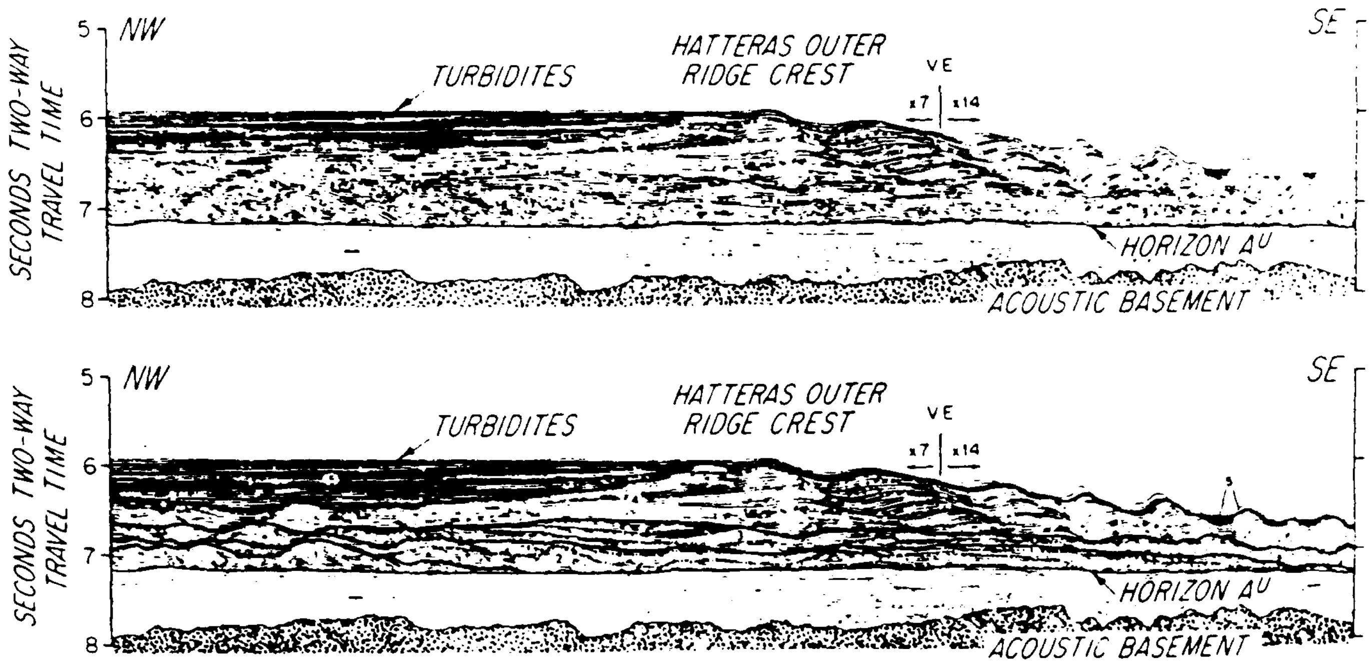



**Figure 30. INTERPRETATION OF A SEISMIC PROFILE IN THE REGION OF THE HATTERAS OUTER RIDGE**

**After Tucholke and Laine (1982)**

The ridge is built upon the $A^U$ unconformity, a prominant acoustic reflector. In the lower profile the accretionary wedges of the ridge are highlighted. Note the ponding of Pleistocene-age turbidites behind the ridge.

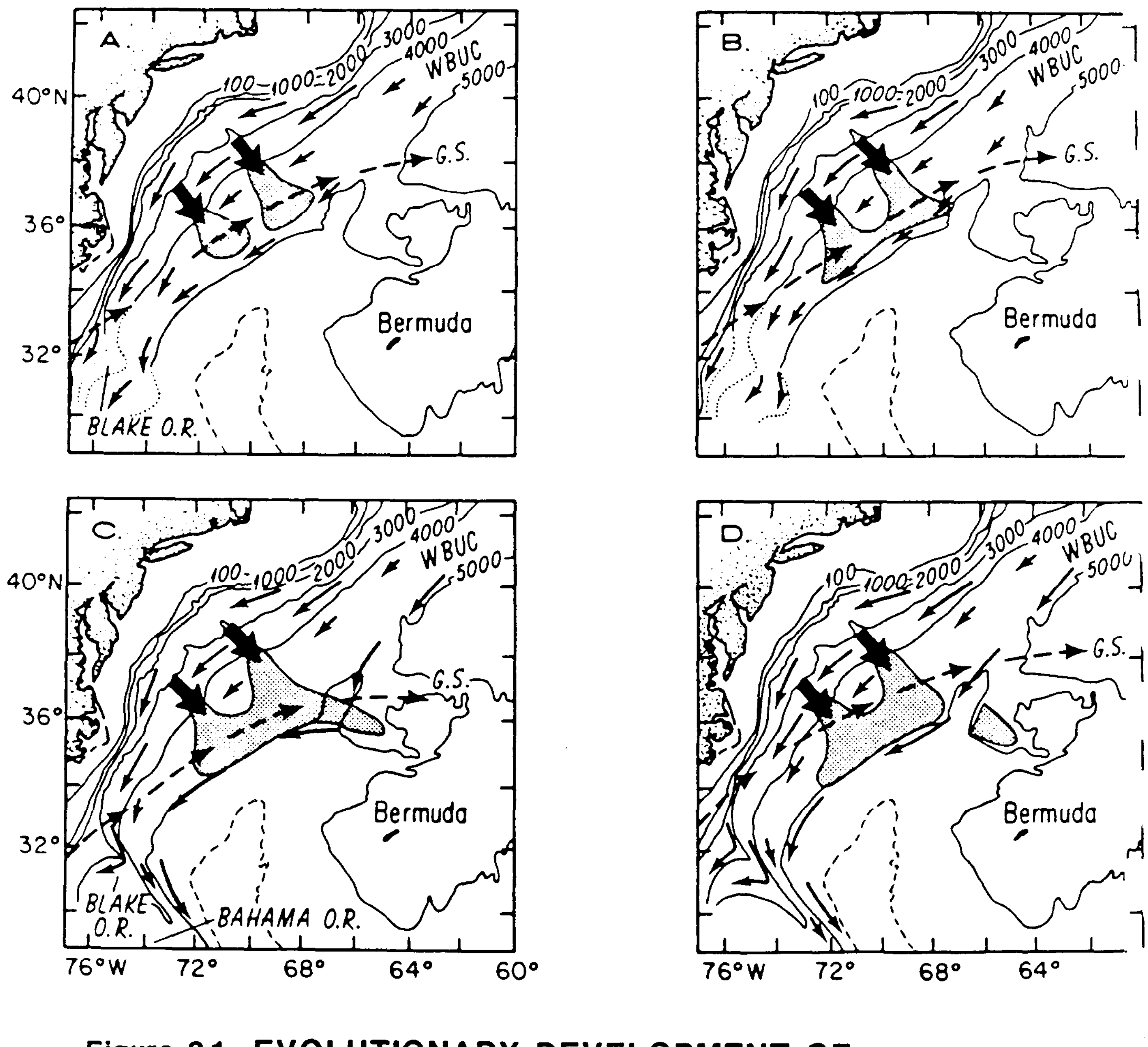



**Figure 31. EVOLUTIONARY DEVELOPMENT OF THE HATTERAS OUTER RIDGE**

**From Tucholke and Laine (1982)**

A. Deposition of deep water fans through turbidity current activity. B. Distribution of sediment parallel to margin contours by deep circulating currents. C. Redistribution of sediment into deepe water through interaction of the Western Boundary Undercurrent (WBUC) and the Gulf Stream (GS). D. Erosion of the sediment by the WBUC. Note that westward of the Hatteras Outer Ridge more turbidites are ponded.

8. The factors which we recognized as important to gas hydrate development at the Blake Outer Ridge appear to also exist at the Hatteras Outer Ridge. Probably the determining factor will be the organic matter flux, an unknown quantity at present.

## Assessment of the Gas Hydrate Resource

Our studies indicate that a wide region of the continental rise southwest of Hudson Canyon are underlain by gas hydrates. We also predict that parts of the upper continental rise and slope regions are also underlain by hydrates as suggested by USGS seismic lines (also J.F. Karlo, pers. comm.). Our conservative estimates of areal extent are as follows:

Class 1 BSR: 12,600 $km^2$ at 2,500 - 3,500 m water depth

Class 2 BSR: 4,250 $km^2$ at 2,500 - 3,600 m water depth

Class 3 BSR: 13,200 $km^2$ at 2,200 - 3,300 m water depth (south of Wilmington Canyon)
1,700 $km^2$ at 2,000 - 2,600 m water depth (north of Hudson Canyon)

These are minimum estimates and do not include potential gas hydrates beneath the continental slope. Note that at the Blake - Bahama Outer Ridge region, the LDGO studies do not recognize BSRs shallower than 2,200 m water depth whereas the USGS studies have recognized BSRs to 750 m water depth. The discrepancy is principally due to the areal coverage of USGS versus LDGO seismic lines. We believe a similar situation may exist at the Baltimore Canyon Trough region.

The total area underlain by gas hydrates is determined by the interpretation of the various BSR classes. Two different interpretations are possible. First, the intermittent nature of Class 2 and 3 reflections indicates an intermittent zone of gas hydrates; second, the Class 2 and 3 reflections indicate an intermittent underlying gas zone but a continuous hydrate zone. Because the Class 2 and 3 reflections appear to correspond to regions of surface erosion, we have previously argued that the hydrate zone may only be intermittently underlain by gas. We therefore accept the second interpretation, which may therefore provide an optimistic assessment of hydrate extent. The total area underlain by hydrates is approximately 30,000 $km^2$ between 2,000 - 3,600 m of water south of Hudson Canyon. If gas hydrates exist beneath the slope region this figure may increase to 45,000 - 50,000 $km^2$ or about one half the area of gas hydrates beneath the Blake Outer Ridge.

We have calculated the volume of gas in place for the lower gas hydrate zone assuming that this is the most economically attractive target. We also have assumed an average volume porosity of 35% and various hydrate distributions as indicated.

Disseminated gas hydrate (100% pore filling):
$56\ m^3/m^3$ ($2\ MCF/m^3$) of sediment

Nodular gas hydrate (50% sediment; 50% hydrate):
$80\ m^3/m^3$ ($2.8\ MCF/m^3$) of sediment

Massive gas hydrate (30% sediment; 70% hydrate):
$113\ m^3/m^3$ ($4\ MCF/m^3$) of sediment

These values are based on gas volumes at wellhead. Using the calculated areal extent of 30,000 $km^2$, the rise in the Baltimore Canyon region would contain at least $2.9 \times 10^{11}\ m^3$ (21 TCF) of gas from a disseminated lower zone one meter thick. Although the hydrate zone would not be continuous over the entire 30,000 $km^2$ area, such an assumption is consistent with the approximate nature of the other factors used in this calculation.

We have also concluded that in the typical hemipelagic argillaceous sediments expected in the continental slope and rise region, the effect of bedding geometry relative to hydrate seal will have a minimum effect on trapping gas beneath the hydrate zone. Instead, we would emphasize the potential for trapping gas in suitably permeable sediments as a result of small undulations in the base of the hydrate seal. Such undulations may result from minor variations in the local heat flow because the vertical distribution of the gas hydrate zone is sensitive to this parameter. In effect, local heat flow variations develop "structure" on the hydrate base. Let us suppose, for the sake of illustration, that an undulation developed at the base of the hydrate zone, covering an area of 1 square kilometer and having 6 meters of closure. Such a geometric arrangement would be difficult to resolve seismically but would act as a "structural" trap for underlying free gas. The total volume within this structure is $3 \times 10^6\ m^3$ and, assuming a sediment porosity of 35%, the total pore volume is $1.05 \times 10^6\ m^3$. Again, for illustrative purposes, assume the pore fluid is composed of 10% free gas, then the volume of trapped gas will be $1.05 \times 10^5\ m^3/km^2$. This is equivalent to approximately 3 $MMCF/km^2$ under reservoir conditions. Obviously, if the undulation covered a larger area, greater gas volumes would be trapped. If future detailed studies of the hydrate base region do demonstrate structure, then the above calculation is easily reworked using more realistic values for closure and areal extent. We emphasize, however, that it is unrealistic to calculate gas in place based upon gas saturations in excess of 10% unless it can be demonstrated that the gas is released from massive or nodular gas hydrate zones. As we have already stated, the development of high gas saturations from dissociation of gas hydrate lean sediment requires gas columns 1,700 m high.

## PART III

## DISCUSSION AND CONCLUSIONS

The geological history of the Baltimore Canyon Trough and environs has been described in terms of the tectonic and thermal evolution of the U.S. Atlantic Continental Margin since Early Jurassic breakup. The focus of sedimentation was within the Baltimore Canyon Trough, which has accumulated almost 15,000 m of clastic sediment within its deepest part beneath the present continental shelf. A prominent carbonate buildup can be recognized on the USGS seismic lines beneath the present upper continental slope and represents the position of the Jurassic and Early Cretaceous shelf edge which subsequently moved landward.

The Mesozoic development of a large deltaic complex behind the carbonate shelf edge was replaced in the Tertiary by open oceanic conditions, but deltaic sedimentation was reestablished in the Miocene as a series of prograding clastic wedges. Throughout the evolution of the margin, fine-grained sediments were deposited on the continental slope and rise and were occasionally interbedded with turbidites as a result of lowering of sea level during the Tertiary and Quaternary.

Gas hydrates have been inferred to occur beneath the present continental rise, based upon the widespread occurrence of BSRs on seismic profiles. An estimate of the areal extent is approximately 30,000 $km^2$ but this does not include the potential for other gas hydrate occurrences beneath the continental slope. The distribution of gas hydrates may also be affected by the widespread sediment instability on the continental slope and rise which resulted in mass movement of sediment into deeper water. Sediment movements involving up to 100 m are considered possible. The evolutionary history indicates that the gas hydrate zone and underlying gassy sediments are probably fine-grained argillaceous lithologies which may show a wide range of compaction. The potential for more porous sediments exists near the shelf slope break and along those parts of the continental rise containing deep-water turbidite fans. Gas hydrates may also occur within the Hatteras Outer Ridge, based upon its similar evolutionary history to the Blake Outer Ridge. The critical parameter in this instance is probably the organic matter flux during the development of the ridge.

A critical evaluation of likely hydrodynamic conditions beneath the continental slope and rise is not encouraging with regard to the widespread development of gas reservoirs in argillaceous sediment. If the gas reservoirs develop by the usual method of pore fluid displacement, then 1,700 m of sediment containing dispersed gas is required to provide the exceedingly high displacement pressures. Alternately, gas reservoirs may develop by dissociation of a lower gas hydrate zone enriched in the hydrate phase. Such a situation would not require pore fluid displacement and the gas volume would depend upon the disseminated, nodular, or massive nature of the lower gas hydrate zone.

A simplistic model has been developed whereby the rate of growth of the lower gas hydrate zone can be calculated as a function of permeability. The model cannot predict the development of nodular or massive gas hydrates which require special permeability conditions to be stabilized.

An analysis of the relationship between clastic and organic fluxes suggests that the continental slope and rise region has been only mildly anoxic throughout the margin evolution. The anoxia probably developed as a result of sedimentation rate and is limited to the shallow sediment regime. The organic matter flux is comparable or lower than that at the Blake Outer Ridge and cannot support extensive bacterial methanogenesis. It appears unlikely that organic rich sediments will be found along the continental slope or rise, although an organic matter "spike" in the late Tertiary may be a major source of methane within the hydrate zone.

In addition to the above discussion the following should also be considered:

1. An extensive zone of gas hydrates is inferred to exist beneath the continental rise in the vicinity of the Baltimore Canyon Trough, based on the presence of BSRs. The zone may also extend beneath the continental slope based on the USGS seismic lines. The maximum areal extent of gas hydrate development may be 50,000 $km^2$. A minimum extent of 30,000 $km^2$ is likely. Evidence for gas hydrate presence is limited to BSRs on seismic profiles, but we emphasize the paucity of information for the slope and rise environments.

2. The stabilization of gas hydrates is considered to be due to a relatively high sedimentation rate over the slope and rise (comparable to the Blake - Bahama Outer Ridge), low bottom water temperature, marginally sufficient organic matter flux, and a low to moderate geothermal gradient (3 - 3.6°C/100 m).

3. The organic matter flux is comparable to or lower than that observed at the Blake - Bahama Outer Ridge. Consequently, the development of gas hydrates through bacterial methanogenesis is limited to about 5% of pore volume.

4. The organic matter flux in the continental rise environment is considered too low to support bacterial methanogenesis excepting those regions, e.g. Hatteras Outer Ridge, where sediment and organic matter redeposition have occurred.

5. Gas reservoirs beneath a hydrate seal probably develop through dissociation of gas hydrate if the lower hydrate zone contains a high proportion of the hydrate phase. Severe restrictions apply to the development of gas reservoirs in argillaceous sediments as a result of gas migration.

6. It is suggested that gas trapping may result from subtle variations in the geometry of the hydrate base in response to minor variations in local heat flow.

7. The gas potential for the hydrate zone is calculated at 85 x $10^{10}m^3$ (30 TCF) from a lower zone one meter thick. A gas reservoir beneath a 6 m closure covering about 250 $km^2$ (100 $mi.^2$) would

   contain approximately 1 TCF of gas at standard temperature and procedure (STP).

8. The relationship between gas hydrate formation and diagenetic mineral formation cannot be evaluated at this site because of the lack of core information in appropriate locations.

9. The relation of pore fluid chemistry to gas hydrate formation cannot be evaluated due to the lack of information on pore fluids.

10. A thermal history analysis confirms the potential for thermogenic gas generation beneath the slope and upper rise. It is considered that the slope is the most favorable region for thermal hydrocarbon generation based upon the thermal regime and the probability of maximum organic matter flux in the slope environment. The thermal potential beneath the rise is considered marginal based upon the thermal regime and the low organic matter flux.

11. The data upon which this report are based are heavily biased towards the shallower parts of the Baltimore Canyon Trough, which then have to be extrapolated to the slope and rise environment. The amount of useful geological data for the continental slope and rise region is small and clearly must be augmented by more information. Any future program of study focused specifically on the gas hydrate potential should be sited within the region of Class 1 BSRs between Hudson and Wilmington Canyons, requiring a drill ship with deep-water drilling potential.

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## APPENDIX

## MARINE GEOPHYSICAL DATA AVAILABLE* IN NAUTICAL MILES
## From 38°N to 40°N and 69°W to 75°W

### Lamont-Doherty Geological Observatory

| Cruise/Leg | Gravity | Magnetic | Seismic |
|---|---|---|---|
| C0812 | - | - | 218.0 |
| C0901 | - | - | 159.0 |
| C1001 | - | - | 116.1 |
| C1012 | - | - | 262.2 |
| C1101 | - | - | 135.4 |
| C1112 | - | - | 229.9 |
| C1201 | - | - | 112.0 |
| C1613 | - | - | 176.6 |
| C1701 | - | - | 71.2 |
| C1806 | - | - | 142.1 |
| C1902 | - | - | 204.9 |
| C1903 | - | - | 525.1 |
| C1904 | - | - | 181.2 |
| C1906 | - | - | 95.4 |
| C1907 | - | - | 157.2 |
| C0913 | - | - | 86.7 |
| V1717 | - | - | 249.6 |
| V1801 | - | - | 237.7 |
| V1819 | - | - | 495.8 |
| V1901 | - | - | 168.2 |
| V1913 | - | - | 176.8 |
| V2001 | - | - | 180.9 |
| V2013 | - | - | 210.2 |
| V2101 | - | - | 90.4 |
| V2114 | - | - | 196.4 |
| V2201 | - | - | 106.4 |
| V2207 | - | - | 262.6 |
| V2301 | - | - | 63.2 |
| V2307 | - | - | 224.1 |
| V2401 | - | - | 67.8 |
| V2503 | - | - | 184.6 |
| V2504 | - | - | 259.7 |
| V2601 | - | - | 180.5 |
| V2610 | - | - | 87.3 |
| V2714 | - | - | 90.3 |
| V2801 | - | - | 102.5 |
| V2912 | - | - | 132.0 |
| V3001 | - | - | 331.3 |
| V3002 | - | - | 112.9 |
| Totals 40 | 0 | 0 | 7347.4 |

* These data available from the National Geophysical Data Center, Boulder, Colorado.

## APPENDIX (cont)

### MARINE GEOPHYSICAL DATA AVAILABLE*
### IN NAUTICAL MILES
### From 38°N to 40°N and 69°W to 75°W

**Woods Hole O.I.**

| | Cruise/Leg | Gravity | Magnetic | Seismic |
|---|---|---|---|---|
| | CH034L01 | .0 | .0 | 124.6 |
| | CH046L01 | .0 | .0 | 255.1 |
| | CH057L01 | .0 | .0 | 84.4 |
| | CH061L02 | .0 | .0 | 96.0 |
| | CH073 | .0 | .0 | 158.0 |
| | CH075L03 | 179.0 | .0 | 179.7 |
| | CH096L03 | .0 | .0 | 99.2 |
| | CH099L01 | .0 | .0 | 158.2 |
| | CH100L12 | .0 | .0 | 179.7 |
| | A2067L01 | .0 | .0 | 65.2 |
| | A2075L01 | .0 | .0 | 34.6 |
| | A2091L02 | .0 | .0 | 32.6 |
| | A2096L01 | .0 | .0 | 294.4 |
| | A2097L01 | .0 | .0 | 113.1 |
| Totals | 40 | 0 | 0 | 7347.4 |

**National Oceanic Atmospheric Administration (NOAA)**

| | Cruise/Leg | Gravity | Magnetic | Seismic |
|---|---|---|---|---|
| | AREA 1A | - | - | 66.0 |
| | AREA 1B | - | - | 79.1 |
| | AREA A/B | - | - | 74.3 |
| Totals | 3 | 0 | 0 | 219.4 |

* These data available from the National Geophysical Data Center, Boulder, Colorado.

## APPENDIX (cont)

### MARINE GEOPHYSICAL DATA AVAILABLE*
### IN NAUTICAL MILES
### From 38°N to 40°N and 69°W to 75°W

#### U.S. Army

| | Cruise/Leg | Gravity | Magnetic | Seismic |
|---|---|---|---|---|
| | | - | - | 405.5 |
| Totals | 1 | 0 | 0 | 405.5 |

#### U.S. Geological Survey

| | Cruise/Leg | Gravity | Magnetic | Seismic |
|---|---|---|---|---|
| | ECT18-38 | - | - | 678.6 |
| | 75 | - | - | 101.8 |
| | ECST9-10 | - | - | 165.5 |
| | ECST7-13 | - | - | 306.6 |
| | E CST1-3 | - | - | 136.1 |
| | E CST4-6 | - | - | 147.8 |
| | MTM 0101 | - | - | 759.7 |
| | MTM 0102 | - | - | 320.1 |
| | A208901 | - | - | 985.8 |
| | A208902 | - | - | 1239.8 |
| | A208903 | - | - | 596.7 |
| | A208904 | - | - | 1039.9 |
| | ECT14-17 | - | - | 268.3 |
| Totals | 13 | 0 | 0 | 6746.3 |

#### Scripps Oceanographic Institute

| | Cruise/Leg | Gravity | Magnetic | Seismic |
|---|---|---|---|---|
| | DSDP11GC | - | - | 401.2 |
| Totals | 1 | 0 | 0 | 401.2 |

* These data available from the National Geophysical Data Center, Boulder, Colorado.

## APPENDIX (cont)

### MARINE GEOPHYSICAL DATA AVAILABLE*
### IN NAUTICAL MILES
### From 38°N to 40°N and 69°W to 75°W

#### University of Rhode Island

| | Cruise/Leg | Gravity | Magnetic | Seismic |
|---|---|---|---|---|
| | TR009 | - | .0 | 573.0 |
| | TR027 | - | 316.0 | 316.0 |
| | TR034 | - | .0 | 234.0 |
| | TR051 | - | .0 | 48.1 |
| | TR083 | - | .0 | 1465.6 |
| | TR099 | - | .0 | 1597.9 |
| Totals | 6 | 0 | 316.0 | 4234.6 |

#### Mineral Management Service

| | Cruise/Leg | Gravity | Magnetic | Seismic |
|---|---|---|---|---|
| | LSSALE59 | - | - | 4026.3 |
| | LSSALE52 | - | - | 2672.6 |
| | ECOAST79 | - | - | 56.9 |
| Totals | 3 | 0 | 0 | 6755.8 |

| | | | | |
|---|---|---|---|---|
| Grand Totals | | 179.7 | 875.2 | 29463.0 |

* These data available from the National Geophysical Data Center, Boulder, Colorado.